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REGIONAL DISCRIMINATION STUDIES: PHASE III

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This report consists of three parts. Part 1, "Construction Of Regional Ground Truth Data Bases Using Seismic And Infrasound Data" is by Gordon Sorrells, Eugene Herrin, and Jessie Bonner with contributions from Jack Swanson, Sarah Deering and Angela Maddox. Part 2, "Seismic And Infrasound Data Observations At TXAR" is by Jessie Bonner, Sarah Deering, Tao Liu, Jack Swanson and Ileana Tibuleac. Part 3, consists of the Acknowledgments called for by the contract.

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1. CONSTRUCTION OF REGIONAL GROUND TRUTH DATA BASES USING SEISMIC AND INFRASOUND DATA

Gordon Sorrells, Eugene Herrin, and Jessie Bonner
with contributions from Jack Swanson, Sarah Deering and Angela Maddox

1.1 INTRODUCTION

At the present time, there is a continuing interest within the Comprehensive Test Ban Treaty (CTBT) verification community concerning existing capabilities to correctly identify the sources of regional seismic events whose magnitudes are in the range $2.5 < m_b < 4.0$. This interest has been spurred on, in part, by the recognition of the fact that commercial explosions such as quarry or mine blasts can account for a substantial fraction of the regional seismic activity in this magnitude range in many industrialized nations (Richards et al, 1992). Consequently, a variety of seismic methods have been developed to identify the sources of regional seismic signals generated by commercial explosions as well as those generated by earthquakes (cf., Baumgardt and Ziegler, 1988; Bennett et al, 1989, Dysart and Pulli, 1990, Harris, 1991, Hedlin et al, 1989. Stump and Reinke 1988). Experience has demonstrated that successful application of these methods within one region does not guarantee their global applicability. Therefore, it is necessary to demonstrate the credibility of the various source identification techniques on a region by region basis. This is accomplished by applying the method(s) to a set of signals which are representative of the seismicity in the region and whose origins have been independently confirmed as explosions or earthquakes. Such a data set is commonly referred to as a "ground truth" data base.

The independent confirmation of the origins of suspected commercial explosive events is the key technical issue to be resolved during the creation of a ground truth data base. A seismo-acoustic method for the independent confirmation of the sources of regional explosive events is proposed in this report to address this issue. The proposed method is based upon the premises that:

- The vast majority of commercial explosions which are large enough to generate seismic events with magnitudes greater than or equal to mb =2.5 are very likely to be partially vented to the atmosphere; and

- In contrast to contained explosions and earthquakes, a vented explosion will generate an infrasonic signal as well as a seismic signal.

Therefore, in principle, the detection of seismic and infrasonic signals which share a common origin time and epicenter uniquely identifies the source of both as a vented explosion. Experiments to evaluate the seismo-acoustic method were initiated in the fall of 1995 as part of a larger project to develop a "ground truth" data base characterizing the regional seismicity in the vicinity of the TXAR seismic array.

1.2 BACKGROUND

The Lajitas, Texas Seismic Array (TXAR) (Figure 1) is a ten element, short-period seismic array located in the Chihuahuan desert of far West Texas. Commercial explosions appear to be the dominant contributor to the regional seismic activity detected at this site. Figure 2 shows the daily occurrence time distributions for the regional seismic activity detected at LTX, the predecessor of TXAR, during a six week monitoring period in 1991 (Golden et al, 1991). Notice that the occurrence times are strongly concentrated during the daylight hours, primarily in the interval from about 1100 to 2100 hours, local time. This result suggests that the majority of the detected seismic events are the result of commercial blasting. A cursory examination of the TXAR data in the fall of 1995 not only verified this inference, but also demonstrated the existence of several sources which consistently generated regional events with magnitudes greater than m_b = 2.5. Furthermore, it was found that several of these sources were located across the international border in northern Mexico. It is also of interest to note that only a small number of these events were reported in the Reviewed Event Bulletin published by the Center for Monitoring Research. These observations indicated that tests of the seismo-acoustic method could be performed under a scenario that is likely to be frequently encountered in the first years following the entry into force of the CTBT, in which regional seismic signals whose

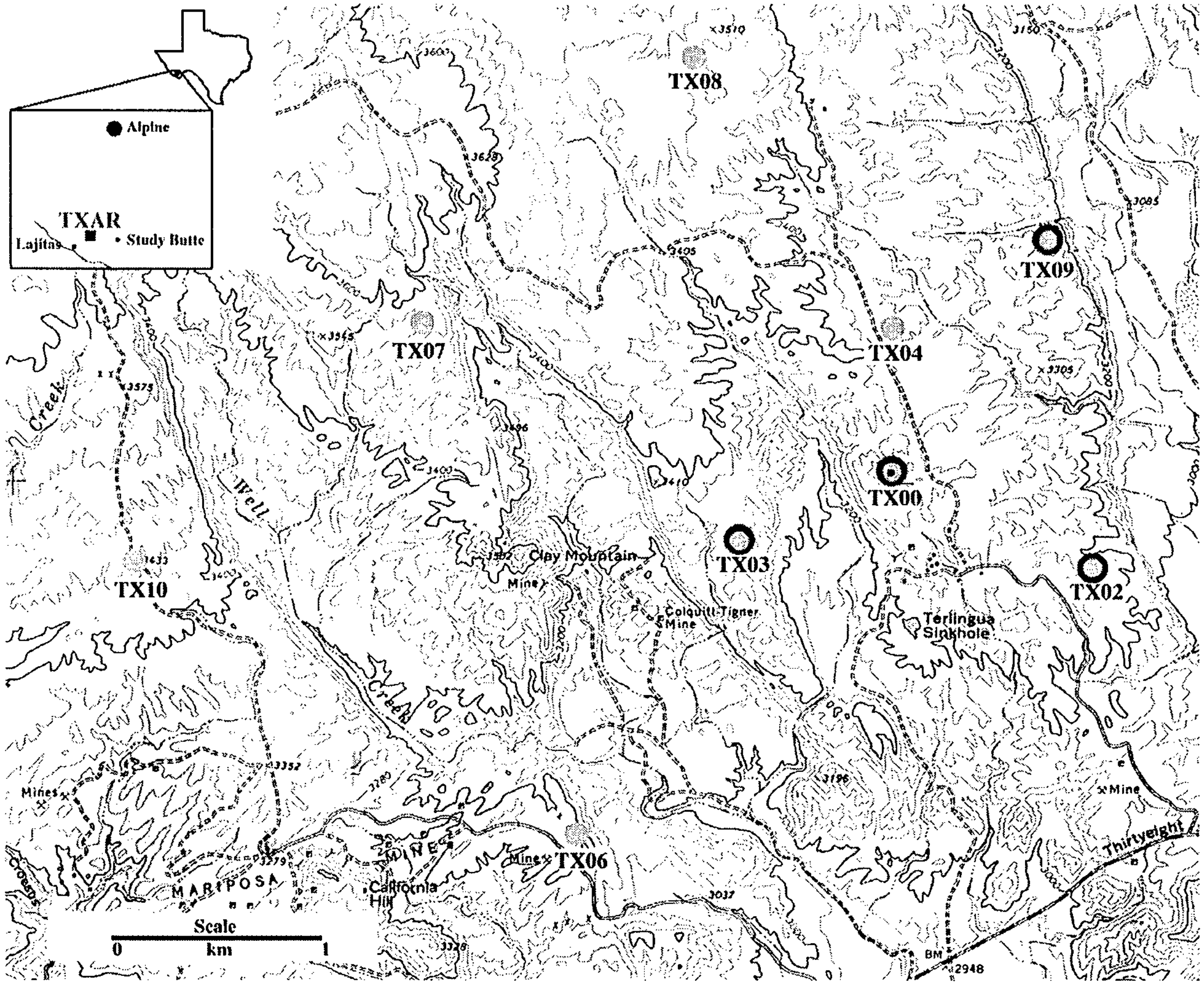

Figure 1. Location of the TXAR array. Acoustic sensors are located at TX00, TX02, TX03 and TX09.

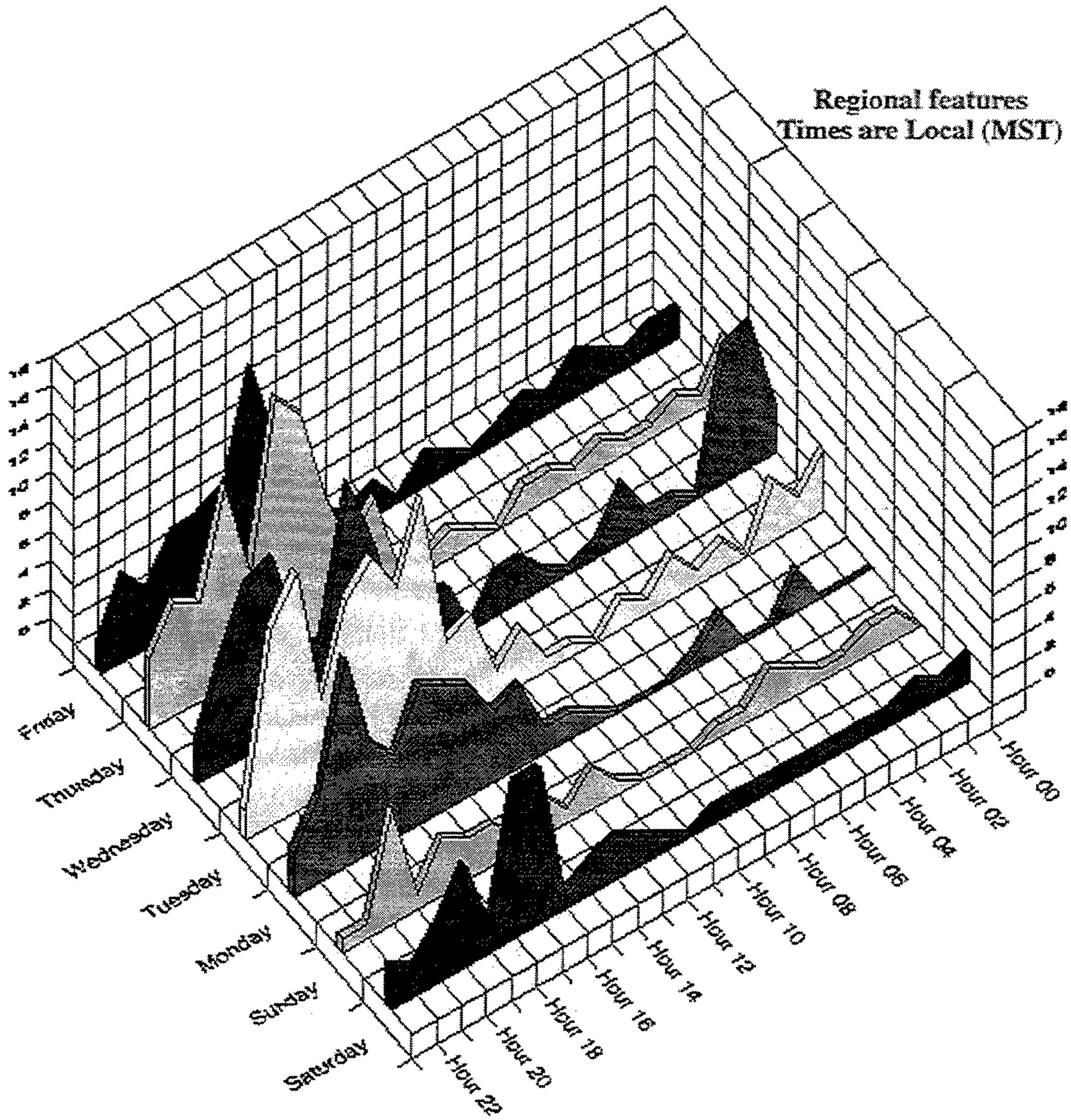

Figure 2. Regional event arrival times at LTX (predessesor to TXAR) during a six week period in 1991.

magnitudes are greater than $m_b = 2.5$ are detected by a single seismic array which is located across an international border from a source(s) of the signals. The correct identification of the origin of these signals is an essential issue to be resolved in the context of monitoring the CTBT. The capabilities of the seismo-acoustic method to resolve this issue are discussed in the following paragraphs.

1.3 IMPLEMENTING THE SEISMO-ACOUSTIC METHOD AT TXAR

Application of the seismo-acoustic method requires the integration of the seismic and infrasound data at some stage in the monitoring process. After considering various options, it was concluded that the acquisition stage was the optimum point for the integration of the two data streams. Integration at this stage offers the opportunity for significant reductions in overall operations, maintenance and data transmission expenses relative to other options, and leads to considerable simplifications in the data processing and analysis procedures required to identify commercial explosions using the seismo-acoustic method. Integration at the acquisition stage was accomplished at TXAR by collocation of the infrasound array at four of the stations in the existing seismic array (Figure 1). This eliminated the accrual of additional capital facilities expenses for the deployment of the infrasound array and its associated data transmission system. In addition, for the application of the seismo-acoustic method, collocation permits the reduction of the data processing and analysis tasks to the identification of one additional phase arrival following the onset of the P wave in the combined records of regional events detected by the two arrays.

Laboratory tests were completed in the fall and winter of 1995 to characterize the pressure sensor to be used for the detection of the infrasonic signals generated by regional commercial explosions. Based upon results of these tests (Hayward, 1996), a modified version of the Validyne Differential Pressure Transducer, model 3050, was selected for use in the TXAR seismo-acoustic experiment. These transducers were acoustically coupled to porous hose pipe arrays in order to reduce the pressure noise caused by local surface winds. The basic characteristics of this system configuration are listed in Table 1. As shown in Figure 3, the results of preliminary field trials of this

- **SENSOR**

  Validyne Model P 3050 pressure sensor

  Whitey SS 22 RF2 shunt valve with micrometer adjustment

- **SPECIFICATIONS**

  Flat to sound pressure from 0.2 sec to 50 sec period

  Sensitivity: 1700 μbars/volt

  System noise re. input: RMS 0.15 μbars in band

  Dynamic Range: 120 dB

- **ARRAY**

  Porous hoses - five - 13 m each into summing volume

- **DATA ACQUISITION**

  40 samples/sec

  24 bit format

  19 bit resolution

- **DATA TRANSMISSION**

  Handled the same way as the seismic data

Table 1. Characteristics for acoustic sensors at TXAR.

configuration indicated that it would yield infrasonic detection thresholds of about a microbar or less in the frequency band of interest (0.5-5.0 hertz) during periods of variable light to calm wind speeds (< 4 m/sec). It was therefore used as the basic sensing component in the 4 element infrasound array deployed for the TXAR seismo-acoustic experiment.

1.4 RESULTS AND DISCUSSION

Two investigations have been carried out to test the seismo-acoustic method's ability to identify regional commercial explosions. The first investigation was simply to determine if any infrasound signals could be detected and associated with a prior suspect seismic event, and was limited to the observation of regional seismic events which occurred during the work-day daylight hours in a time interval extending from 13 April 1996 to 13 May 1996. The results of this study indicated that the pressure amplitudes of the infrasound signals generated by commercial explosions could be as large as a few microbars and could be detected at near-regional distances from the source. It was also found that estimates of infrasound group velocity and azimuth could be successfully used to associate an infrasound signal with a prior seismic signal. Therefore, a second, more ambitious investigation was initiated on 15 July 1996 to detect, locate, and apply the seismo-acoustic method to identify the origin of all seismic events with magnitudes greater than m_b=1 which occurred at regional distances to TXAR. As of 10 August 1996, the results of the second investigation have yielded 179 regional events whose spatial distribution is shown in Figure 4. Locations for the events were determined using Lg-Pn/Pg travel times and backazimuths obtained from frequency-wave number analysis of the array output.

Notice that the majority of the epicenters occur in four major clusters within or near the known mining complexes. The cluster found east-southeast of TXAR at a range of about 300-320 km is approximately coincident with the MICARE (Minera de Carbonifera Rio Escondito) coal mining district located in Coahuila, Mexico near the international border with the United States.

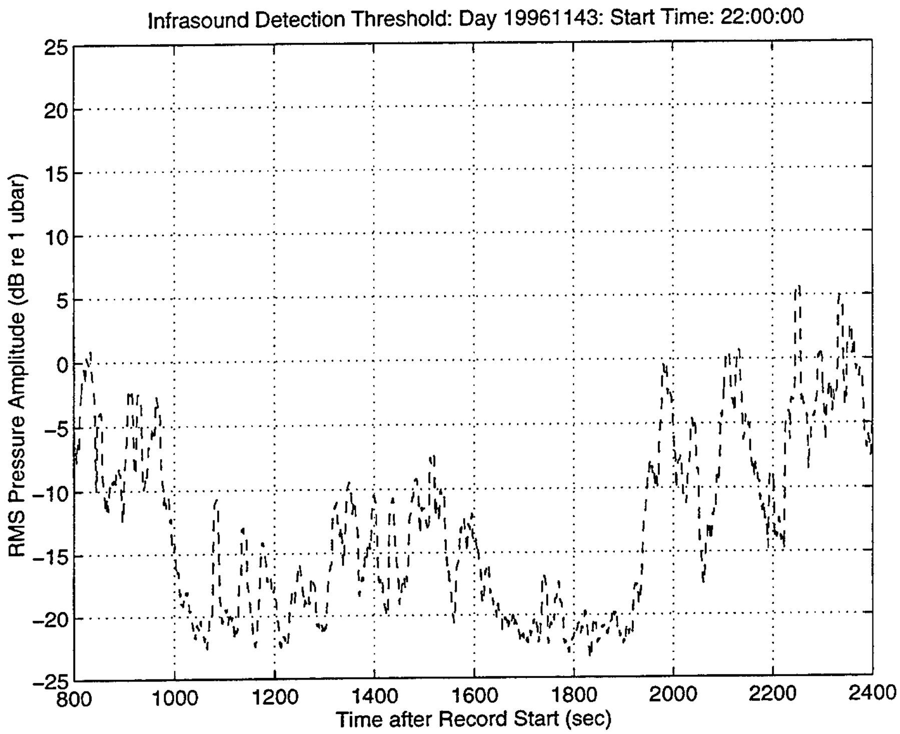

Figure 3. Infrasound detection capabilities at TXAR.

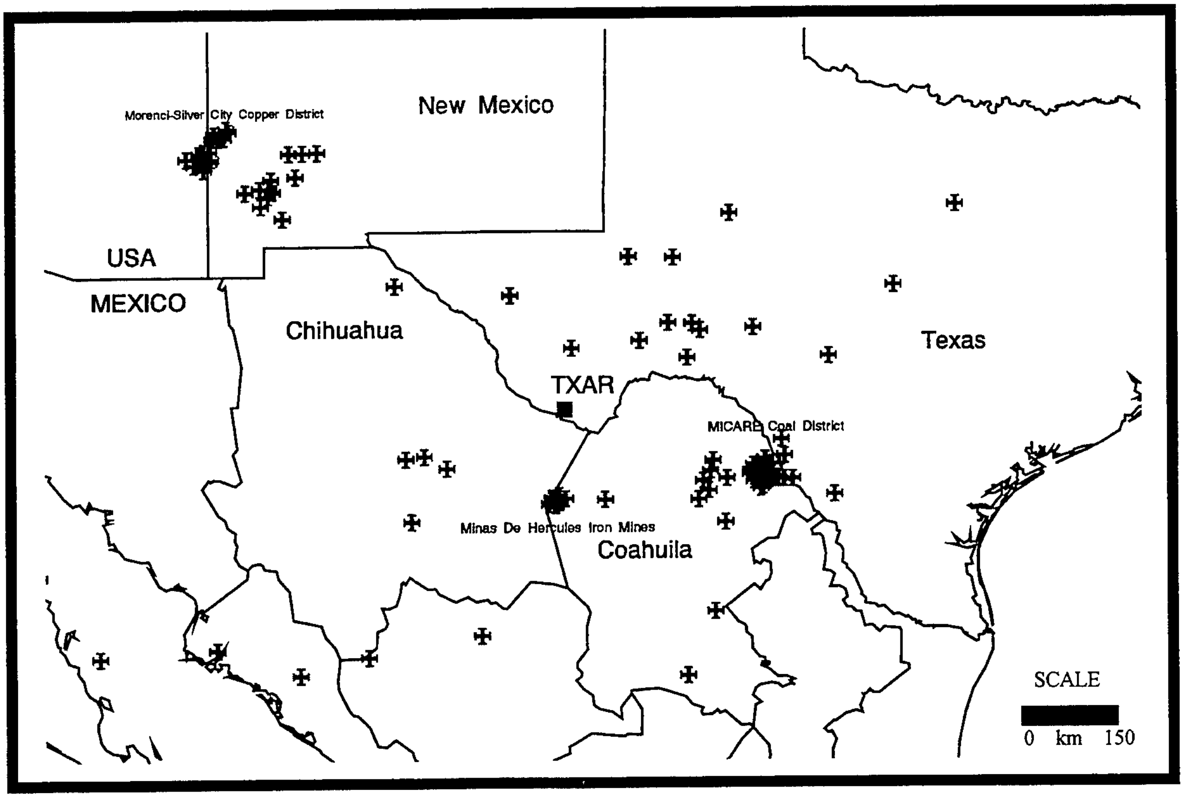

Figure 4. Locations of events recorded at TXAR between July 15, 1996 and August 10, 1996.

The cluster found due south of TXAR at a range of about 140-160 km occurs near the Minas de Hercules iron mines in northern Mexico. The two clusters found about 550-700 km northwest of TXAR approximately overlie the Morenci-Silver City Porphry Copper Mining District in Southeastern Arizona and Southwestern New Mexico. The occurrence time distributions for the seismic events contained in each of the clusters are shown in Figure 5A, 5B and 5C. The majority of the seismic activity within or near each mining complex occurs between 1500 hours and 2300 hours GMT (10:00 AM to 8:00 PM, CDT). This observation, reinforces the suspicion that the events in each of the clusters are the result of commercial explosions. The occurrence times for the activity external to the known mining complexes display (Figure 5D) a subdued, but similar pattern, suggesting isolated explosions unrelated to conventional mining operations may also make a contribution to the regional seismic activity observed at TXAR.

On the basis of these observations approximately 90% of the events detected during the investigation were identified as suspected commercial explosions. The seismo-acoustic method was applied to all events in the data base to confirm the origin of the suspected mine blast events and to identify possible isolated explosive events. The confirmation process required:

1. The visual detection of a signal on at least three of the four infrasonic data channels in a time interval corresponding to a group velocity window of 0.25-0.40 km/sec when referenced to the origin time and location of a prior seismic event.

2. The approximate coincidence of the propagation azimuths of seismic and infrasound signals.

The results of the TXAR seismo-acoustic test are discussed below.

1.4.1 MICARE Coal Mines and West Texas Blasting Activity

The application of these criteria yielded 16 infrasonically confirmed explosions, all of which were located east of TXAR. Eleven of these events occurred within the MICARE cluster (Figure 4). An example of the seismic

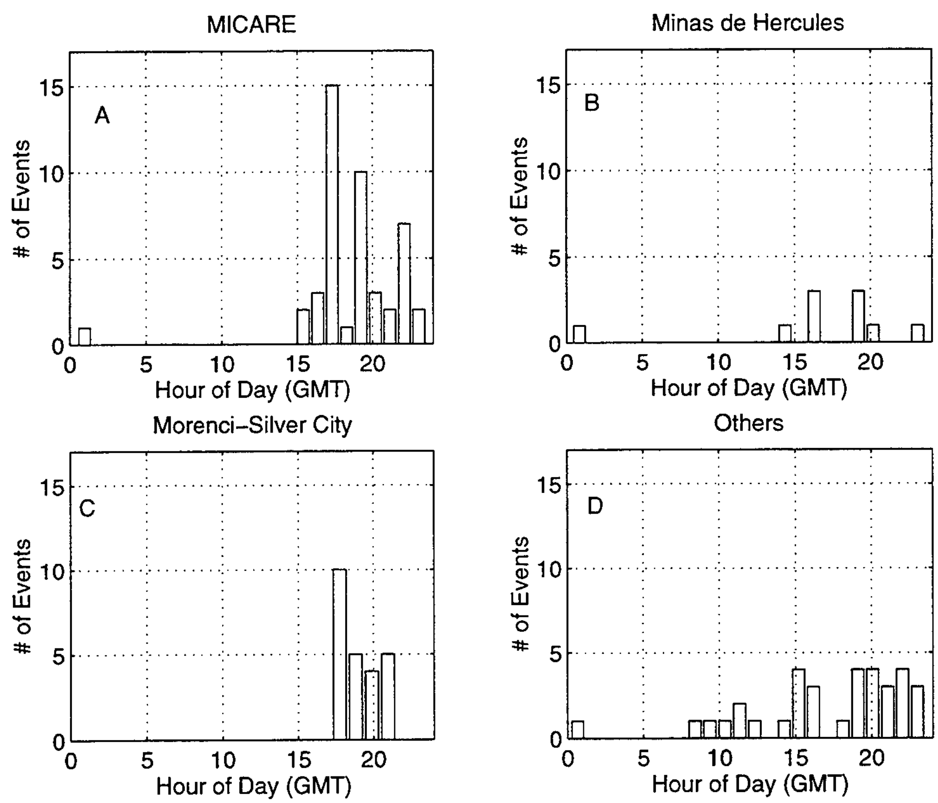

Figure 5. Occurrence times for regional events at TXAR.

signal and the associated infrasound signal generated by one of the confirmed MICARE explosions are shown in Figure 6.

Explosive seismic events with magnitudes in the range $1.5<m_b< 3.5$ are generated within this complex and detected at TXAR at an average rate slightly greater than one per day. It is also important to note that MICARE events with magnitudes greater than $m_b = 2.5$ occur on a weekly to biweekly basis. Thus, records of the MICARE activity provide an ideal data base for the evaluation of the seismo-acoustic source identification method. A sample set consisting of 50 events representative of the activity observed during the summer months was drawn from the MICARE population for a pilot study. The objective of this study was to determine if there was any systematic relationship between the magnitudes of the seismic events and the success rate for the seismo-acoustic method during this time period. The results of the study are summarized in Figure 7. Notice that while the success rate is less than about 20-25% for events with magnitudes less than $m_b = 2.5$, the majority of the events with larger magnitudes are confirmed as explosions by the seismo-acoustic method.

The remaining five infrasonically confirmed explosions were located about 200-250 kilometers northeast of TXAR, well beyond the boundaries of the known mining complexes. Further investigation of these events revealed that two were related to explosions for pipeline construction near Dryden, TX. Two were associated with uncontained explosions for mud pit excavations in the Olsen oil field in Crockett Co. TX, and one was the result of a large quarry blast in Uvalde County, TX.

1.4.2 Minas de Hercules Iron Mines

No infrasound signals were detected from sources at the Minas de Hercules iron mines in northern Mexico. This illustrates the effect of an important spatial constraint to the application of the seismo-acoustic method. While the absence of infrasound detections from this source region are, in part, related to the relatively low magnitudes of seismic events ($m_b < 1.5$), the thermal structure of the atmosphere also plays a significant role. The speed of sound

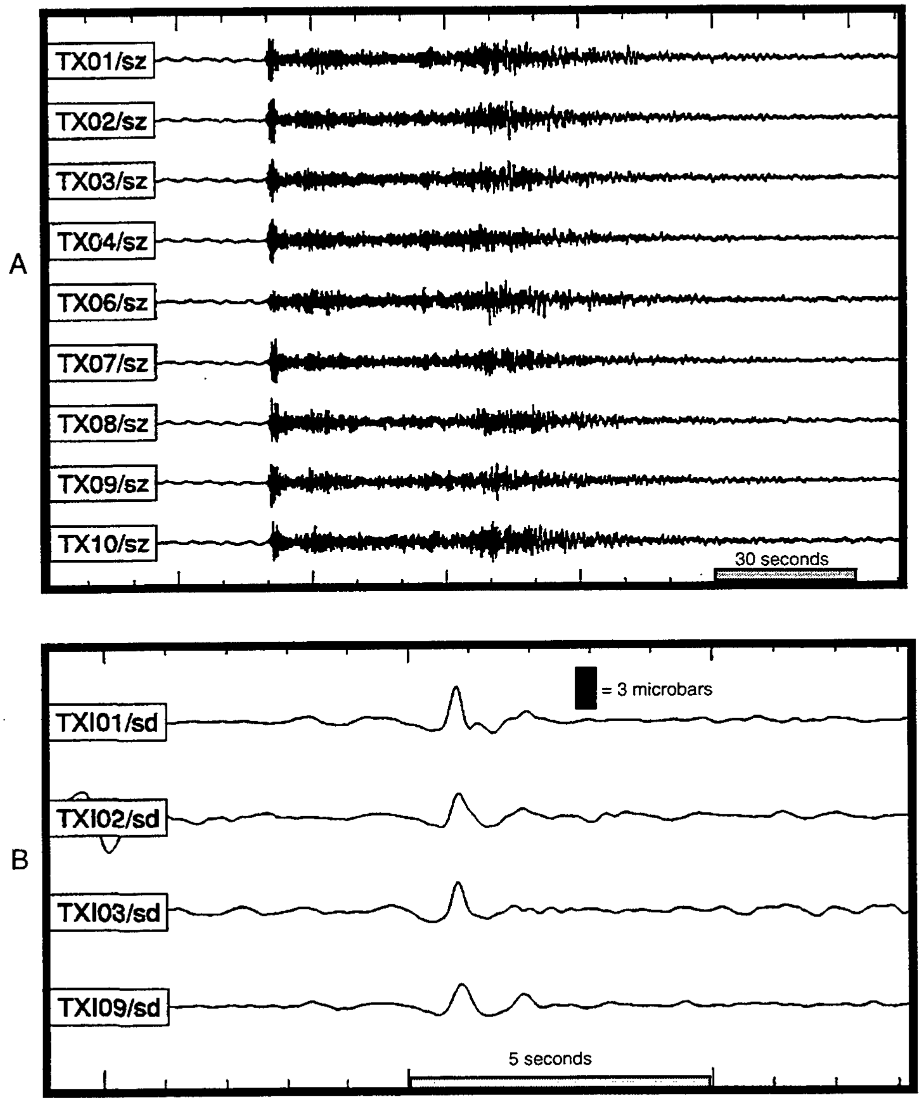

Figure 6. Seismograms (A) and microbarograms (B) from an explosion in the MICARE mining district of northern Mexico.

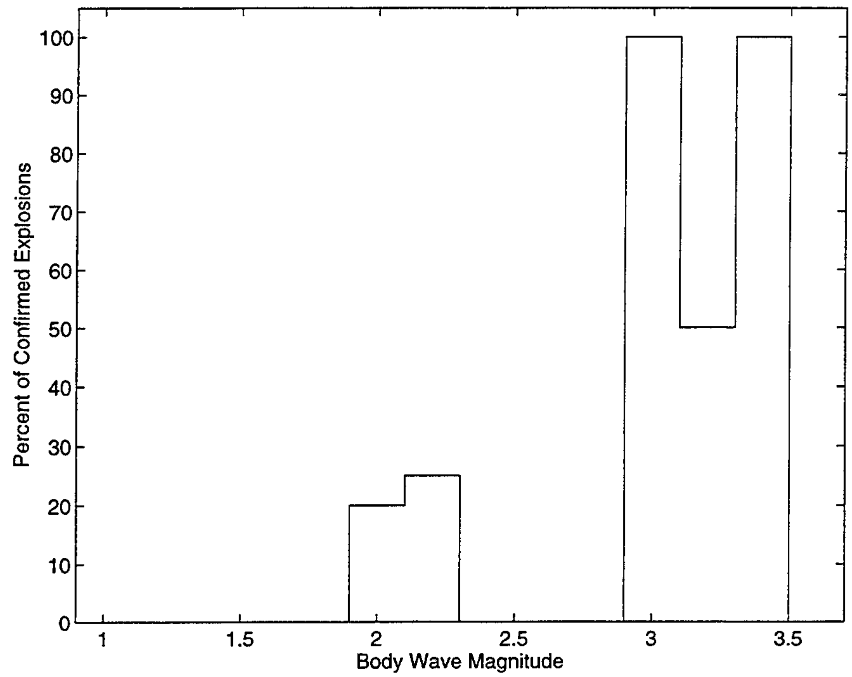

Figure 7. Magnitude-infrasound relations at TXAR.

in air is proportional to the square root of the temperature, therefore, the decrease in temperature with increasing altitude over the first 25-30 kilometers of elevation introduces a "zone of silence" or "shadow zone" surrounding a surface source. The zone typically starts about 50-100 kilometers from the source and extends out to about 175-200 kilometers (Georges and Beasley, 1977). The distance from Minas de Hercules to TXAR is about 150 kilometers, thus placing it well within the zone of silence surrounding this source region. This is believed to be the most likely explanation for the absence of infrasound signal detections at TXAR from explosions at the Minas de Hercules mines. This hypothesis will be tested in the future by placing temporary seismo-acoustic stations at distances outside the "shadow zone".

1.4.3 Arizona and New Mexico Copper Mines

The majority of the seismic events which occurred within the Morenci-Silver City complexes and which were detected at TXAR had magnitudes greater than or equal to m_b=2.4. Since most of the MICARE seismic events in this magnitude range were confirmed as explosions by the detection of associated infrasound signals, it was disappointing to find that there were no similar detections associated with the Morenci-Silver City seismic events. The absence of visually detectable infrasound signals from the Morenci-Silver City complex illustrates the effects of an important temporal constraint to the application of the seismo-acoustic method. It has been recognized that for a given source and observation point the amplitude of regional infrasound signals will be functionally dependent upon the difference between the source-to-receiver azimuth and the azimuth of the zonal stratospheric winds. Calculations by Plantet (1996) predict that the signal strength observed at regional distances from the source will be significantly enhanced on stratospheric paths "downwind" from the source and will be substantially attenuated on stratospheric paths "upwind" of the source. Under extreme conditions the difference between upwind and down wind signal amplitudes can be as much as 30-40 dB. The balanced zonal wind speeds (Newman et al, 1989) representative of mean conditions in the test region are shown in Figure 8.

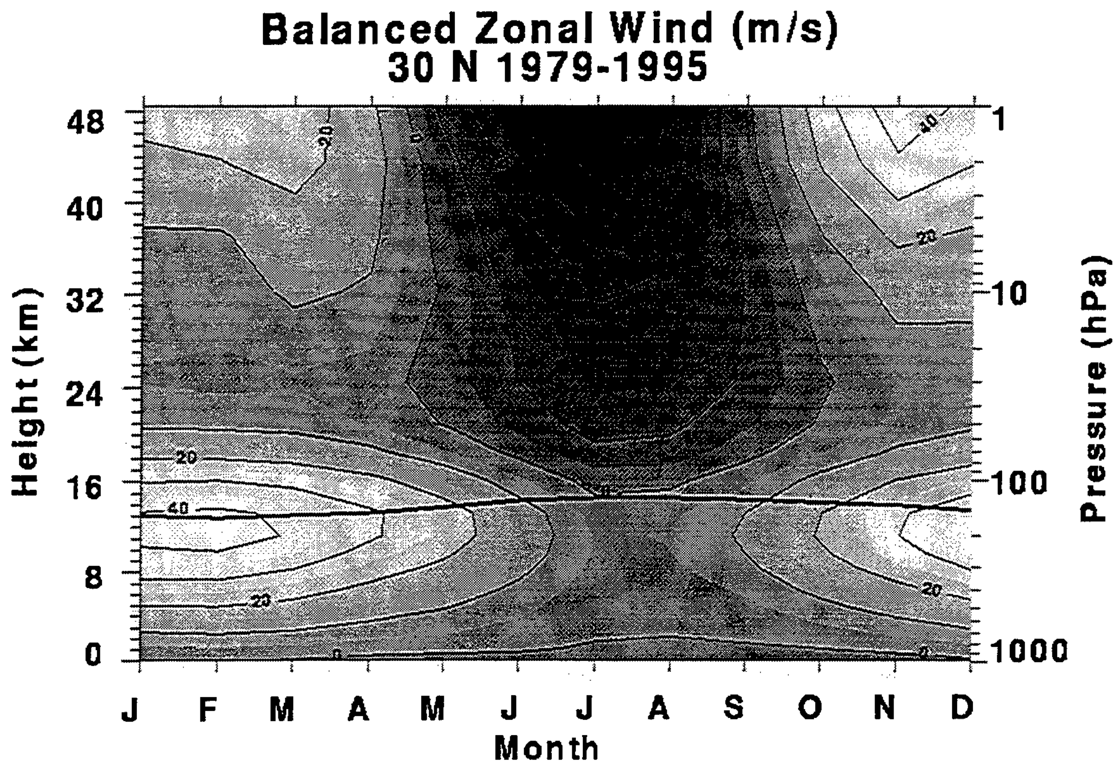

Figure 8. Zonal wind speeds at 30N latitude.

The darker colors show mean zonal winds that are blowing east to west, while the lighter colors indicate that the zonal winds are blowing west to east. During the spring and summer months the winds blow from east to west in the study region, reversing directions during the fall and winter months. It should be recalled that the infrasound data discussed above were acquired during the spring and summer of 1996-- a time interval that places TXAR stratospherically "downwind" of sources at the MICARE mines and stratospherically "upwind" of sources at the Morenci-Silver City mines. Therefore, assuming the validity of the Plantet (1996) predictions, it should come as no surprise that while infrasound signals were detected for the majority of the large explosions at MICARE, none were observed from the Morenci-Silver City explosions of comparable strength in July and August 1996. Finally, it can be seen from Figure 7 that the zonal stratospheric winds are expected to reverse directions in mid-September. If the explanation offered above is correct, then opportunities for the detection of infrasound signals from the Morenci-Silver City explosions should be considerably enhanced after mid-September while detection opportunities for infrasound signals from the MICARE explosions should be diminished. Spot checks of the TXAR data were made in September and October of 1996 to test this prediction. It appears that the last MICARE infrasound detection of 1996 occurred in late September. The first Morenci-Silver City infrasound detection occurred on 11 Oct 1996. The TXAR microbarograms of this event are shown in the lower panel of Figure 8. It was associated with the seismic events whose records are shown in the upper panel. While data must be evaluated over a complete cycle, it seems clear from these results that the zonal stratospheric wind introduces a significant time dependent anisotropy to the detection of regional infrasound signals. It is also important to note that epicentral distance of the Morenci-Silver City event was about 680-700 kilometers. Thus, the acoustic signals shown in Figure 9 are the first experimental data which indicates that the seismo-acoustic source identification method can be successfully applied at distances greater than a few hundred kilometers.

The 11 Oct 1996 seismograms shown in Figure 9 are result of an open pit explosion from the Phelps-Dodge Tyrone Copper mine west of Silver City,

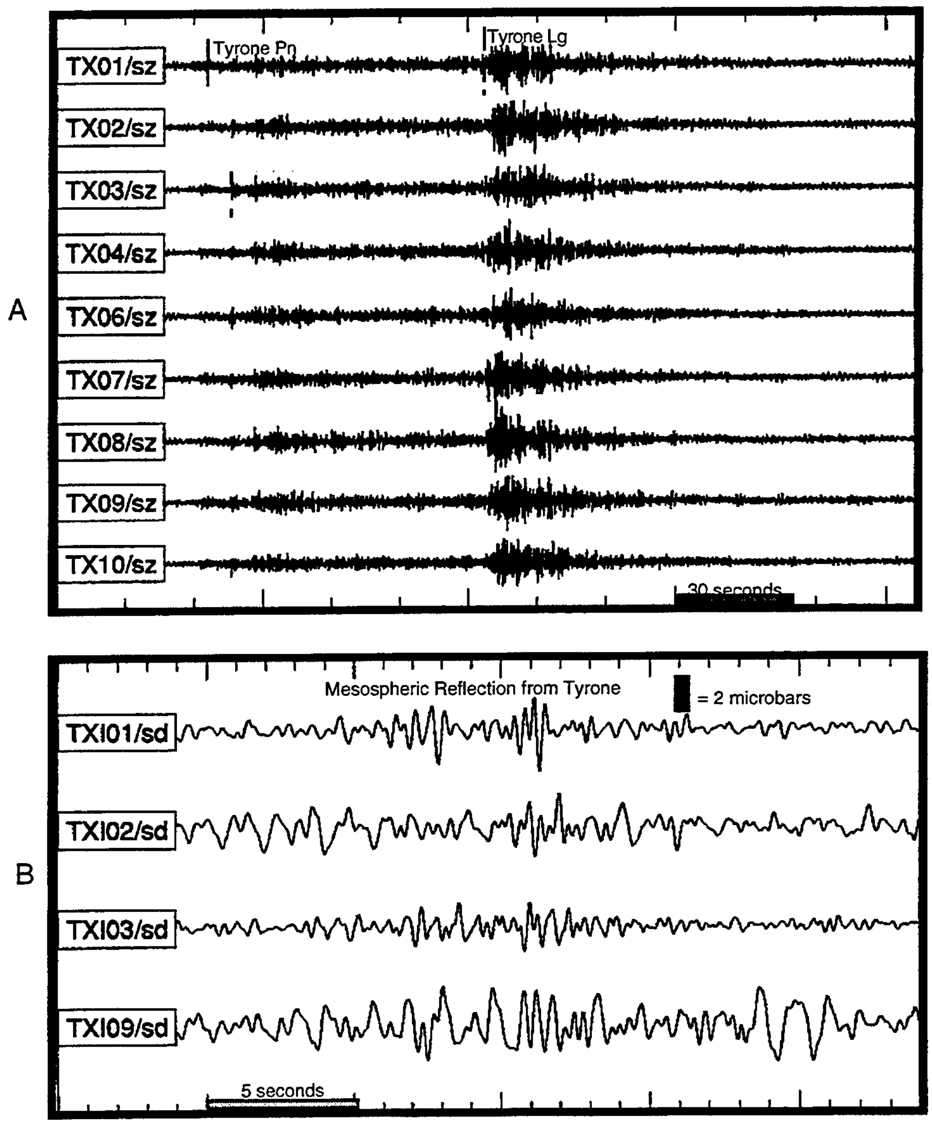

Figure 9. Seismograms (A) and microbarograms (B) from an explosion at the Tyrone Copper mine in western New Mexico.

New Mexico (m_b=2.4) Ray tracing for a model atmosphere composed of three layers (troposphere, stratosphere, and mesosphere) predict three reflected acoustic arrivals at epicentral distances greater than 320 km (Blanc et al, 1996). Since the Tyrone-TXAR distance is 580 km, TXAR should have recorded three acoustic arrivals as a result of the blast, assuming TXAR was stratospherically "downwind" from the mine. In fact, three separate acoustic signals were found to follow the explosion, and Figure 10 shows these infrasonic arrivals plotted as function of epicentral distance and time from the origin of the event. Also shown are the expected arrival times for reflected acoustic signals in the absence of wind (Blanc et al, 1996). By comparing the predicted arrival times with the observed, we were able to distinguish the cause of each signal, thus the microbarograms in the lower panel of Figure 9 show the mesospheric reflection from the Tyrone blast. The fact that each arrival occurs before the predicted arrival times indicates that TXAR was downwind of the event, confirming the prediction of Figure 8.

1.5 CONCLUSIONS

The results of the TXAR seismo-acoustic experiment illustrate that infrasound signals generated by commercial explosions are detectable in the 0.5-5.0 hertz bandwidth and can be observed at distances up at least 680 kilometers from the source. Furthermore, it may be inferred from these results that the sources of the majority of commercial explosive seismic events will be identifiable by the detection of associated infrasound signals when:

- the magnitudes of the seismic events are greater than about m_b =2.5
- their source to receiver distances exceed about 175-200 kilometers;
- the events occur during a time period and at locations such that the reception point is located stratospherically "downwind" from the sources.

It follows then that application of the seismo-acoustic source identification method to data acquired over a complete stratospheric zonal wind cycle at a

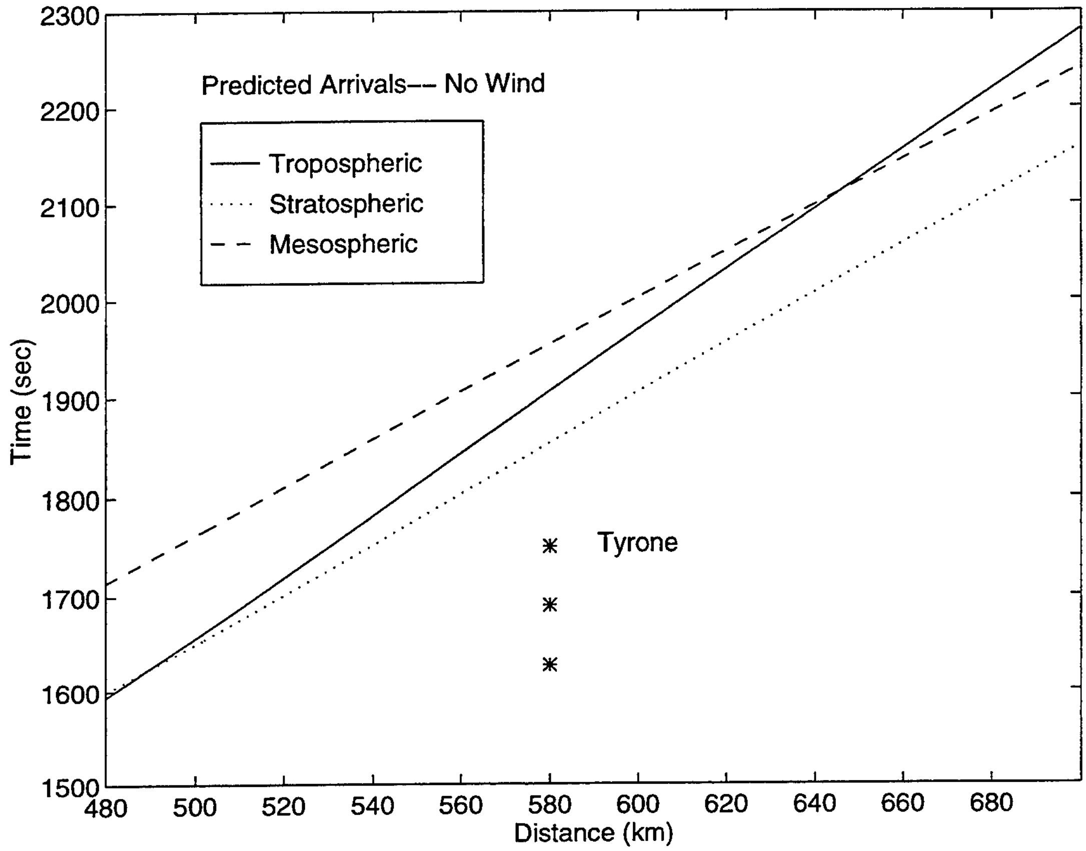

Figure 10. Arrival times for the infrasound signals from the Tyrone explosion.

particular site will provide the information required to construct a ground truth data base. This data base will accurately identify the sources of the seismic events that occur at regional distances to the site whose magnitudes are found in a range that is of significance to the verification of the CTBT.

1.6 ACKNOWLEDGMENTS

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2. SEISMIC AND INFRASOUND DATA OBSERVATIONS AT TXAR

Jessie Bonner, Sarah Deering, Tao Liu, Jack Swanson and Ileana Tibuleac

2.1 OVERVIEW

Constructing a regional "ground-truth" database for the southwestern United States and northern Mexico using the seismo-acoustic method is a primary research goal for seismic analysts at Southern Methodist University. At present, analysts at SMU are conducting the second Seismo-Acoustic Ground Truth (SAGTII) test. Sorrells et al (1997 and section A of this report) summarize the results of the first test. The purposes of this paper are to;

- present preliminary results for SAGTII, and
- catalog observations of local to near-regional seismic and infrasound data recorded at TXAR.

2.2 SEISMO-ACOUSTIC GROUND TRUTHING AT TXAR

The second seismic and acoustic ground truth test using the TXAR array in West Texas (see map, Figure 1) is currently underway. A goal of this test is to determine the percentage of seismic events recorded at TXAR between November 1-December 15, 1996 that had associated acoustic signals. During this time period, stratospheric zonal winds blew from west to east, thus enhancing the opportunity to record infrasound signals from the west of TXAR. This temporal factor also decreased the chance of recording infrasound signals originating east of the array, an inference confirmed by the preliminary results of SAGTII. To date, infrasound signals have only been associated with regional events from the west of the array for a time period between 1 and 7 November 1996. Some of the observations from this time period are presented in the following paragraphs.

Figure 11 shows the seismic signal from an explosion at the Phelps-Dodge Tyrone copper mine in western New Mexico on November 4, 1996 as recorded by the TXAR array. The backazimuth from the array to this quarry is 312 degrees at a distance of 580 km, thus placing TXAR stratospherically

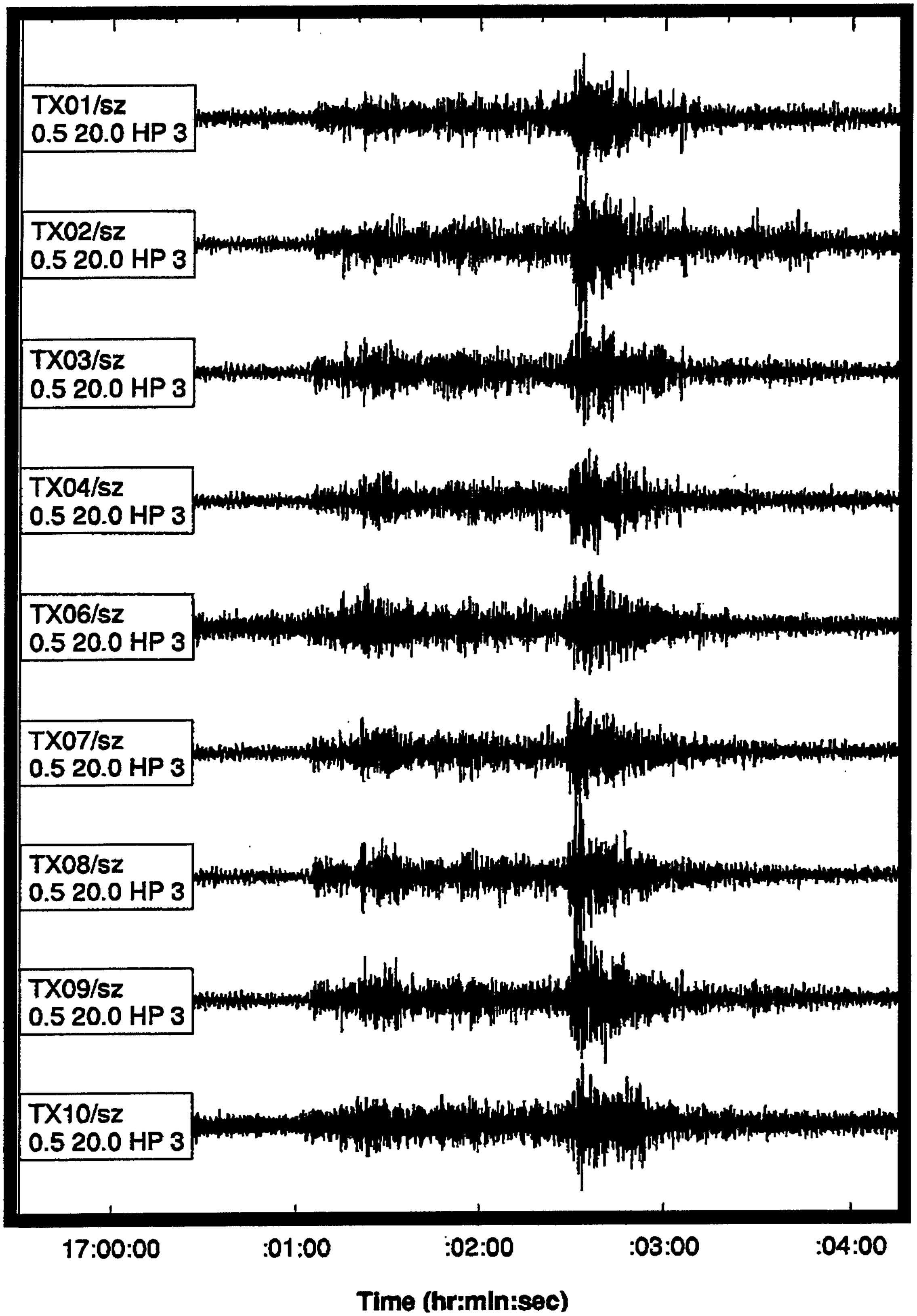

Figure 11. Seismograms from a Tyrone explosion on Nov. 4, 1996 as recorded at TXAR.

downwind of Tyrone. Confirmation of the blast by the engineers at Tyrone showed the blast to be a simultaneous explosion, in which, because the bench was small, involved the detonation of 50 holes with no delays. This fact resulted in a relatively small amount of explosives (35 tons of ANFO) generating a m_{Lg} of 2.7. When compared to blasts with delays from the same quarry, explosives amounts on the order of 55 tons are needed to generate a regional seismic signal with equivalent magnitude. Waveform tags show the filters used in processing the data.

Figure 12 shows five infrasound signals recorded at TXAR from the November 4, 1996 Tyrone blast (upper plot). Each event was transformed to the frequency-wavenumber (F-K) domain to determine the azimuth of arrival (backazimuth) and phase velocity across the array (lower plot). Table 2 shows the result of the F-K processing on the five infrasound arrivals. The phase velocities increase for each successive event, suggesting increasingly greater altitudes at which the rays are turning.

Table 2. Characteristics for the November 4, 1996 Tyrone Blast acoustics.

Time	**Phase Velocity (km/sec)**	**Backazimth**
17:26:57	0.34	301
17:28:11	0.345	303
17:29:18	0.35	302
17:30:36	0.352	302
17:31:48	0.36	302

Figure 13 is a plot of the signals for the first acoustic arrival (arrival time 17:26:57) from the November 4, 1996 Tyrone event aligned to a slowness of 2.90 sec/km and at a backazimuth of 301 degrees. Also shown is the beam formed by the aligned traces of the TXAR acoustic array.

Figure 14 shows the results of processing infrasound arrivals using semblance, which is a measure of the coherence between traces. Semblance processing is accomplished by aligning the traces to a certain phase velocity and azimuth as determined by F-K analysis. A smoothing window is then

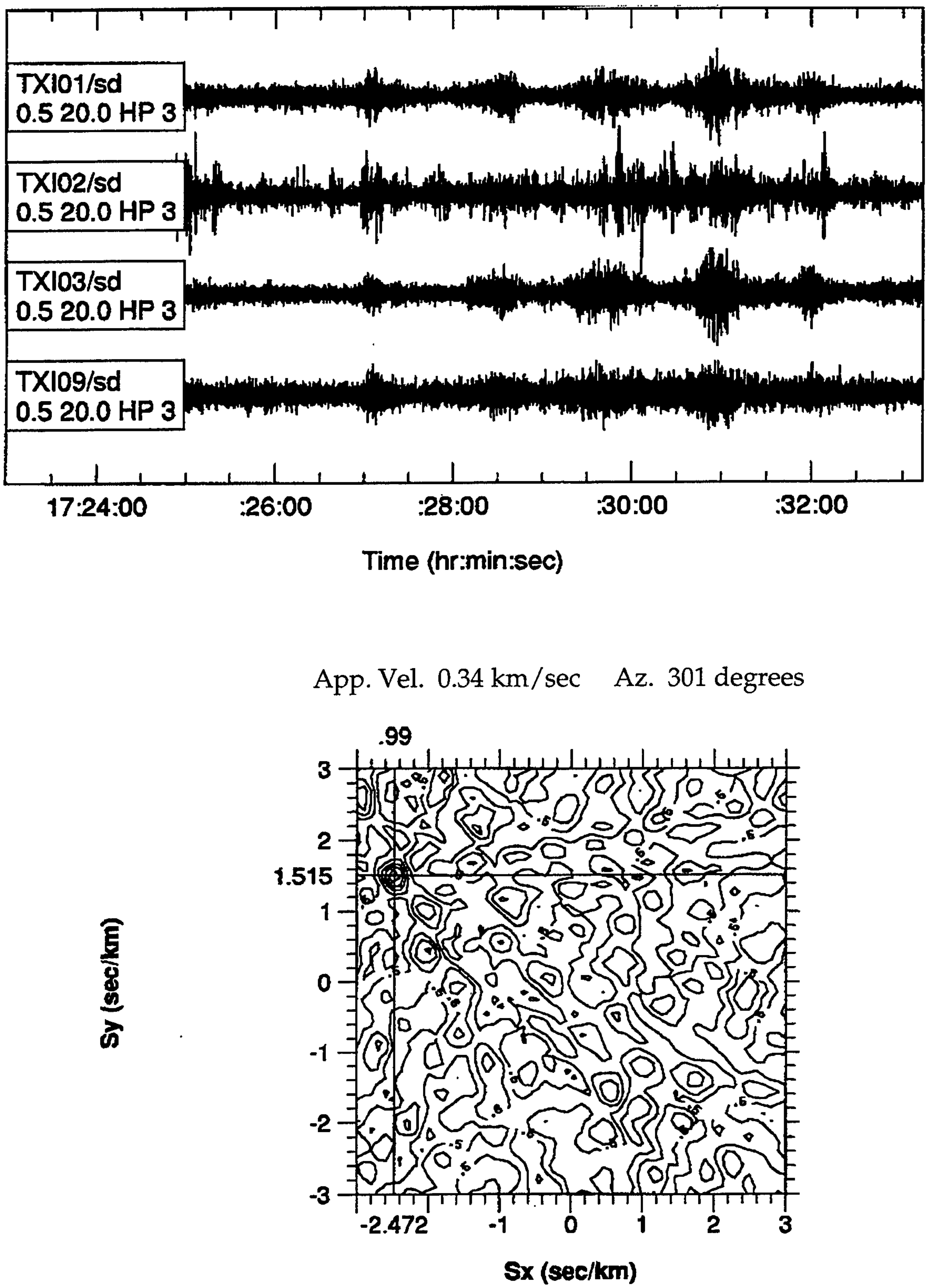

Figure 12. (Upper Plot) Infrasound signals from the Nov. 4, 1996 Tyrone event. (Lower Plot) F-K analysis of infrasound signal at 17:26:57.

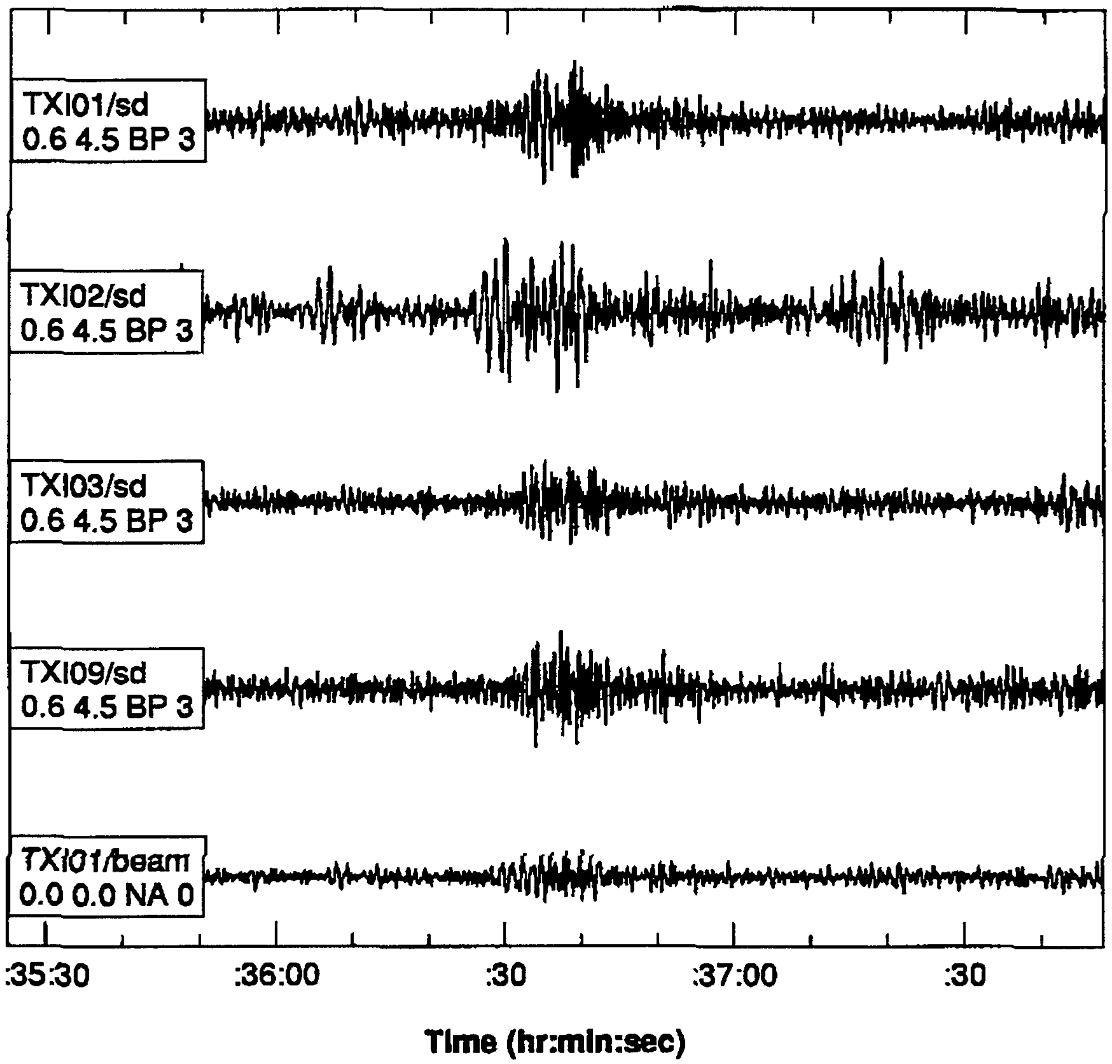

Figure 13. Infrasound signal from the Nov. 4, 1996 Tyrone event (arrival time 17:26:57) aligned to a slowness of 2.9 sec/km and at a backazimuth of 301 degrees. Also shown is the beam formed by the aligned traces of the acoustic array.

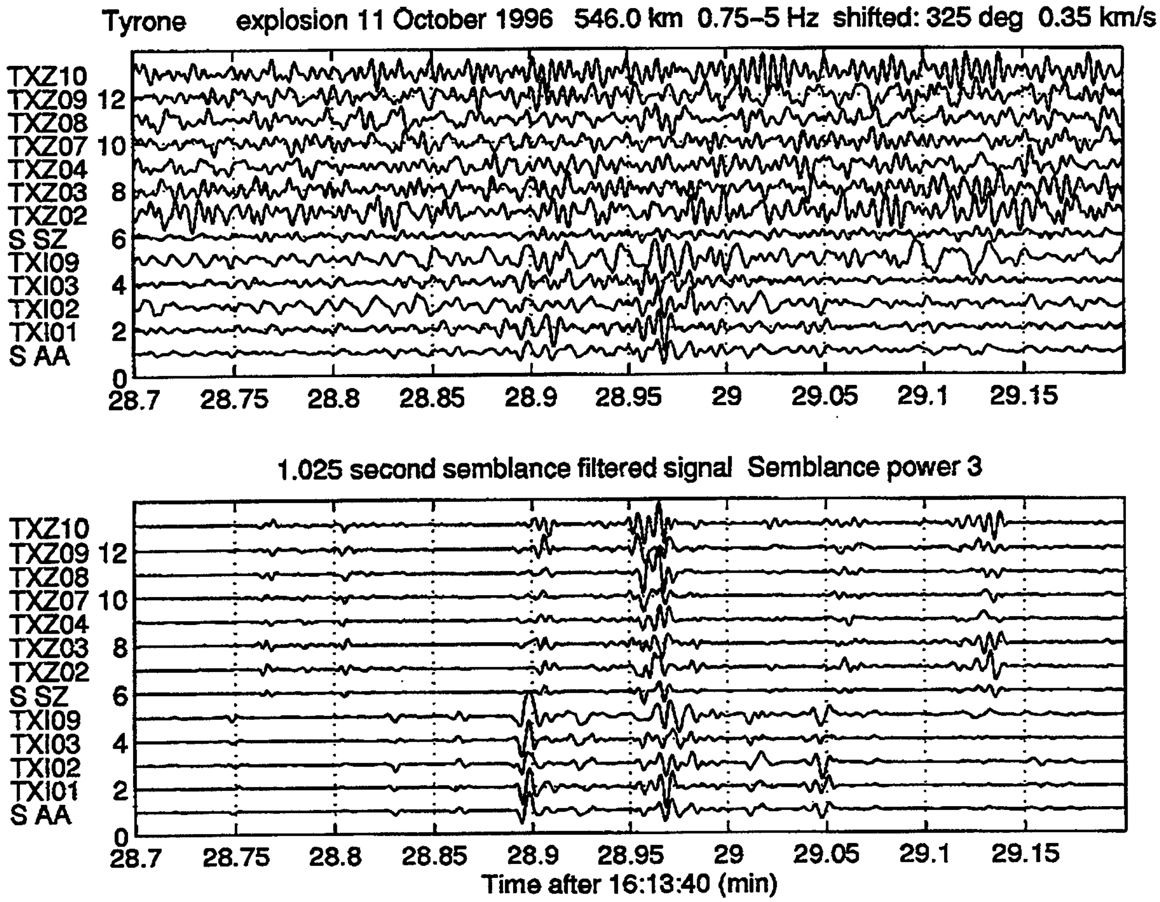

Figure 14. Results of semblance processing on seismo-acoustic data at TXAR.

applied to the data such that the semblance can be calculated as a function of time over this window. The semblance is defined as the energy of the beam divided by the mean energy of beam components within the smoothing window. The trace amplitudes are then multiplied by some power (e.g. 3) of the semblance and plotted. The source of the event was a Tyrone explosion (m_{Lg} 2.6) on October 11, 1996. The upper plot shows the TXAR seismic and acoustic array data aligned to 0.35 km/sec, shifted to a backazimuth of 325 degrees, and band pass filtered between 0.75 and 5 Hz. Note the lack of visible seismo-acoustics on the seismic channels (TXZ02-TXZ10). However, after calculating the semblance between each trace (bottom plot), the signature of the infrasound event on the seismic channels is noted. Similar processing on acoustics signals recorded during SAGTII is underway.

Figure 15 gives the locations for events recorded thus far in SAGTII. While conducting the first ground truth test in the summer of 1996, the MICARE coal mining district in northern Mexico was the most common source of infrasound signals recorded at TXAR. However, the last observed infrasound signals from MICARE occurred in late September. During the winter months, infrasound signals are more readily observed from events west of TXAR.

Figure 16 shows the magnitude relations for the events recorded at TXAR during the first ground truth test in the summer of 1996. The graph shows that infrasound signals were more likely to be observed on events which had greater m_b that m_{Lg}., where m_b and m_{Lg} are defined as:

$$M_b = -17.0 + \log A/T + 7 \log d$$

and

$$M_{Lg} = -1.73 + 2.56 \log d + \log A$$

with

$A \equiv$ (0-P) amplitude in nanometers
$T \equiv$ period in seconds
$d \equiv$ distance in kilometers.

This suggests that events of shorter duration (which perhaps create more P wave energy and sharper source spectra) are more efficient in generating infrasonics that propagate to regional distances than ripple-fired explosions

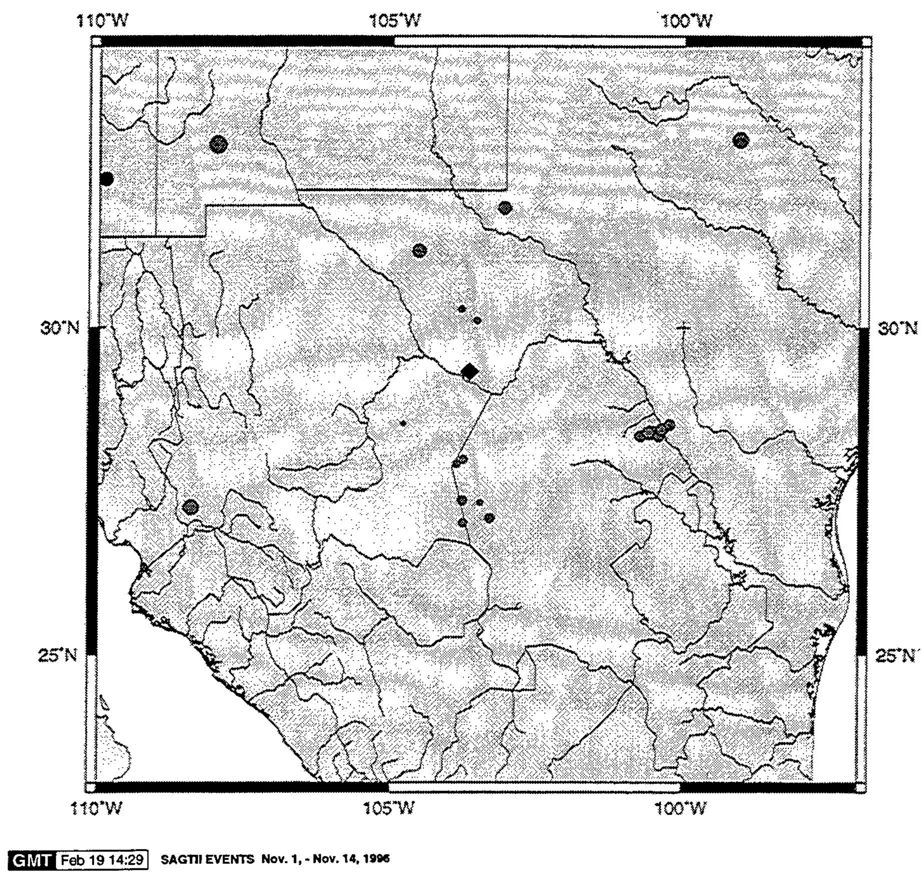

Figure 15. Near-regional events recorded at TXAR between Nov. 1-7, 1996.

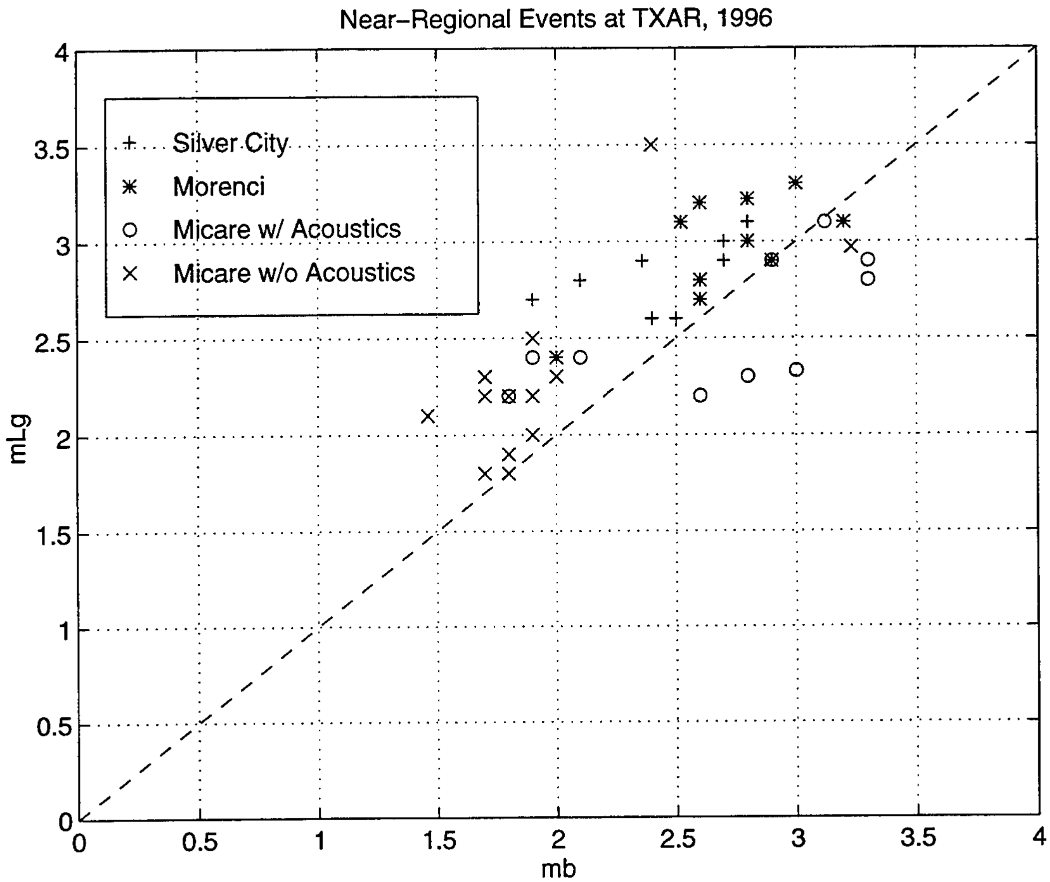

Figure 16. Magnitude relations for events recorded at TXAR between July 1, 1996 and Aug. 15, 1996.

with long delays and scalloped spectra. Thus, a goal of the current ground truth test (SAGTII) is to determine if similar magnitude-infrasonic relations can be observed during the winter months.

Figure 17 shows an infrasound arrival on November 4, 1996 at 16:48:15 with a backazimuth of 300 degrees and phase velocity of 0.35 km/sec. This event was not associated with any seismic signal, thus the source could not be determined. Based upon conversations with the blasters of Cobre Mines in western New Mexico, the infrasound signal could be the result of blasting at their facility. This is typical of Cobre where blasts seem to couple well with the atmosphere but not well into the ground perhaps suggesting some stemming problem. TXAR rarely records a seismic signal from Cobre blasts, however blaster confirmation has led us to infer that unassociated infrasound signals such as this one are indeed from mining operations.

2.3 OBSERVATIONS OF ACOUSTIC AND SEISMIC DATA AT TXAR

During the past year, many interesting events have been recorded and processed at TXAR that are not typical of earthquake or explosion data. Sources for these events range from meteor showers to weather-related phenomena, and include explosions that generate atypical phases such as PnPn. The nature of several of these events pose possibilities for false alarms in the context of a CTBT. Proper identification of such events is necessary to develop "ground-truth" databases for CTBT monitoring stations across the world. The processing and identification of these events as recorded at TXAR are explained in this section.

Figure 18 is a vertical-component seismogram from an explosion (with no delays between rows or holes) at Phelps-Dodge Tyrone in western New Mexico. The inset shows three distinct P wave arrivals. The second of these arrivals is suspected to be the seldom observed PnPn. In fact, PnPn has not been observed on records for ripple-fired blasts originating at the Tyrone mine, which suggests that PnPn observation is inhanced by the presence of a sharp, short-time duration source. Arrival times for the phase are in agreement with those predicated for PnPn by the IASPI model. These explosions, in which the holes are detonated without delays due to a small

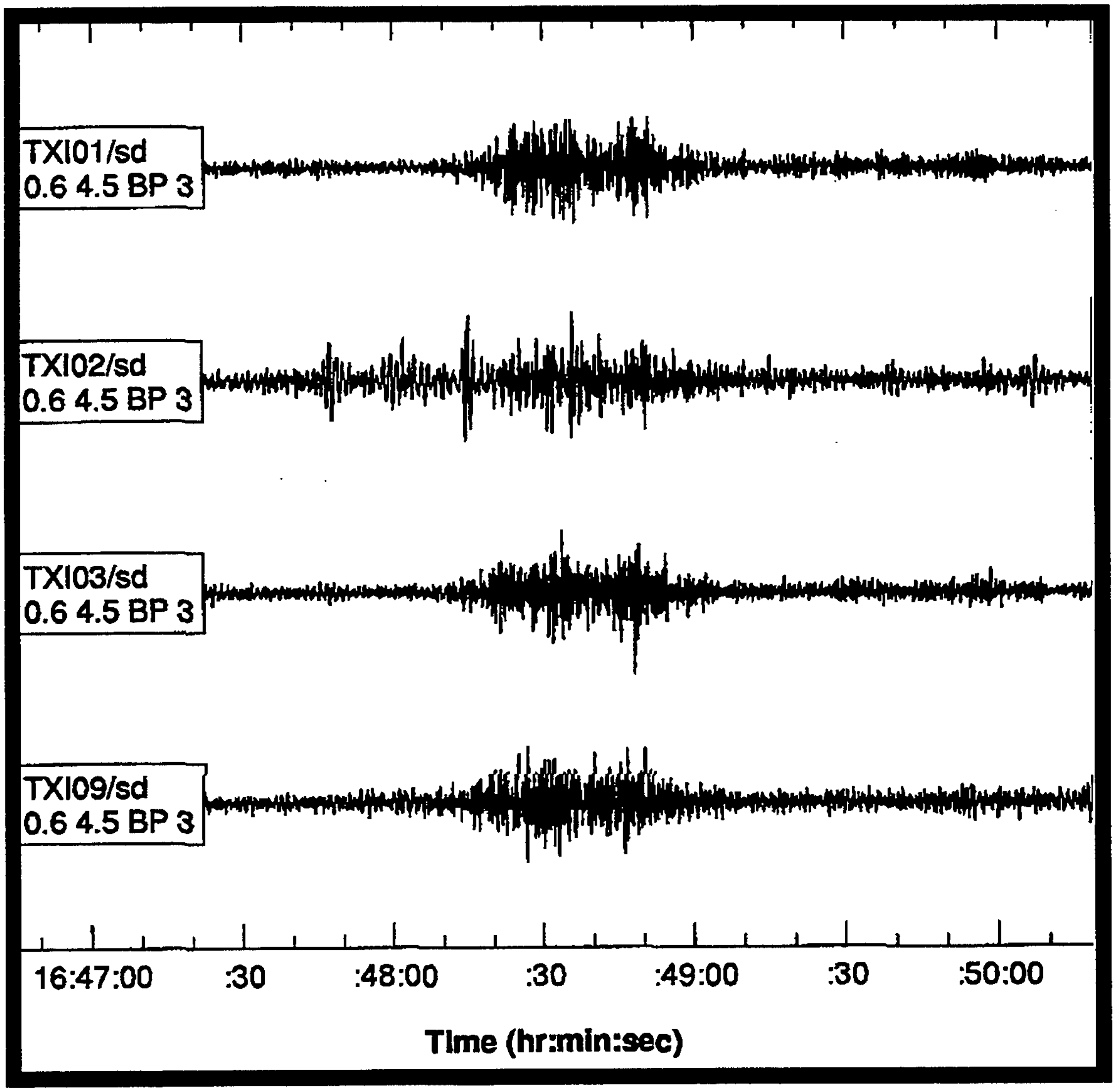

Figure 17. Infrasound signal believed to be from the Cobre Mines of western New Mexico.

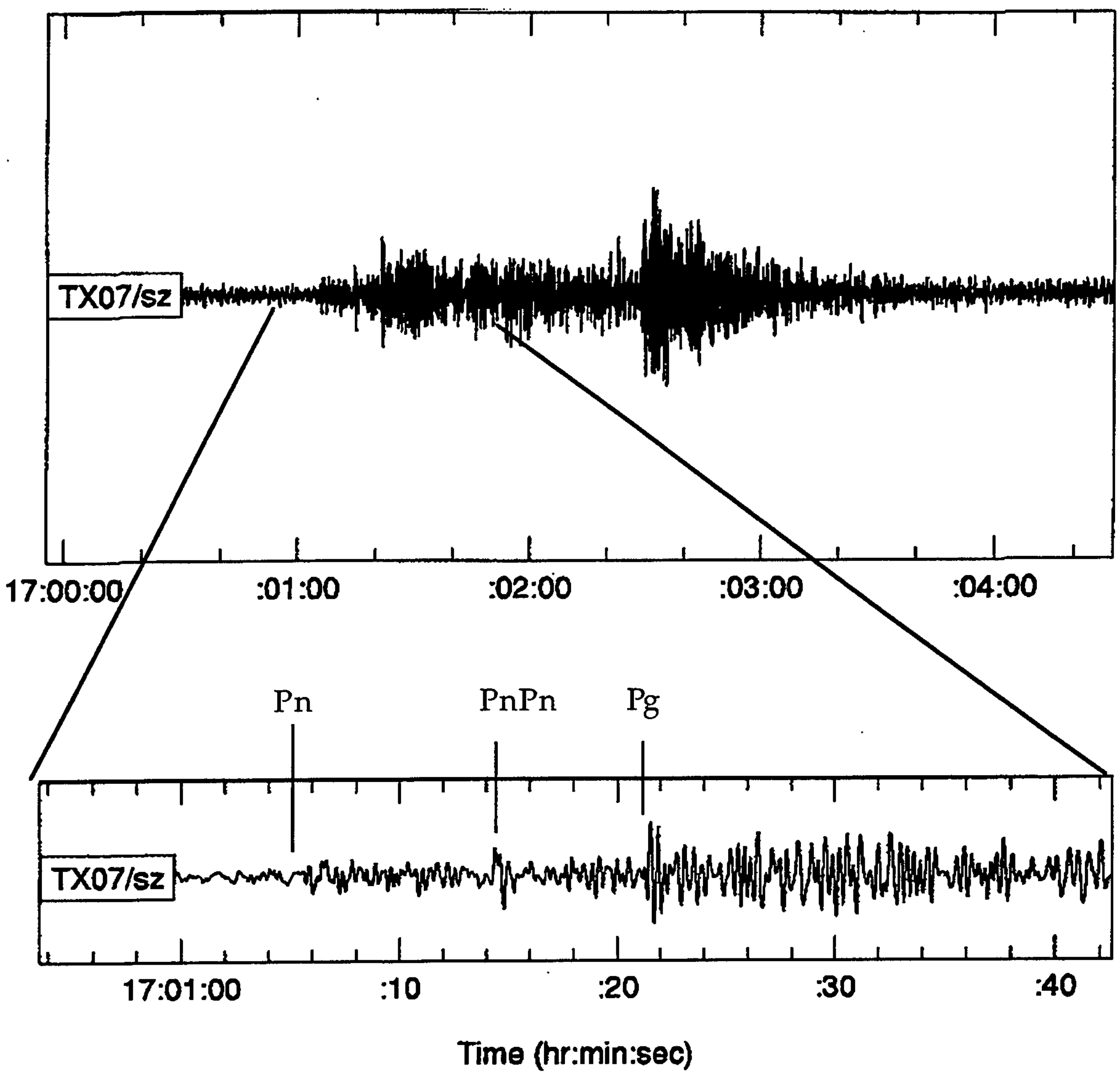

Figure 18. P wave arrivals at TXAR from a Tyrone explosion on Nov. 4, 1996.

topographic bench, are more efficient generators of infrasound signals that traverse regional distances than ripple-fired explosions from the same quarry. Table 3 shows the results of F-K processing of three explosions from Tyrone that generated all three P phases as well as infrasound signals. The true backazimuth from TXAR to the Tyrone mine is 312, thus Pg gives the best estimate of the azimuth. Calibration studies at TXAR by Tibuleac and Herrin (1997) predict the correction to the Pn azimuth for these events to be +7 degrees, which when added to the values in Table 3 bring the Pn estimates within one degree of the true azimuth. The interesting feature in Table 3 is how PnPn varies by as much as 18 degrees off the true azimuth. Because of this fact, it looks as if we have two separate and overlapping events; a) a Pn and a Pg from an explosion with a 312 degree backazimuth to TXAR, and b) a Pn with a 300 degree backazimuth to TXAR (293 + 7 degrees correction). However, repetition of the events and blaster confirmation has proven all three P phases are originating from the same source.

Phenomena such as this could cause false alarms during the CTBT, for it looks like an attempt has been made to hide an event within the coda of another. In fact, discrimination methods that determine events to be quarry blasts based on source duration and/or scalloped spectra would find this event to be an outlier. It is the presence of seismo-acoustics from these events that help distinguish them as an explosion vented to the atmosphere.

Table 3. P wave characteristics of three Tyrone blasts (no-delays)

Date	Pn Vel (km/sec)	Pn Baz	PnPn Vel (km/sec)	PnPn Baz	Pg Vel (km/sec)	Pg Baz
10/11/96	9.6	305	10.3	293	7.2	311
11/04/96	9.7	306	10.1	294	6.9	311
02/11/96	9.7	305	9.7	294	6.9	311

Figure 19 is an example of a new processing technique being developed at SMU whereby signals are decomposed using wavelets. The original signal was decomposed with a level 5, db10 wavelet (left). The signal was then denoised (right upper plot), and then the original and threshold coefficients were calculated and plotted (right lower plot). Lighter colors correspond to

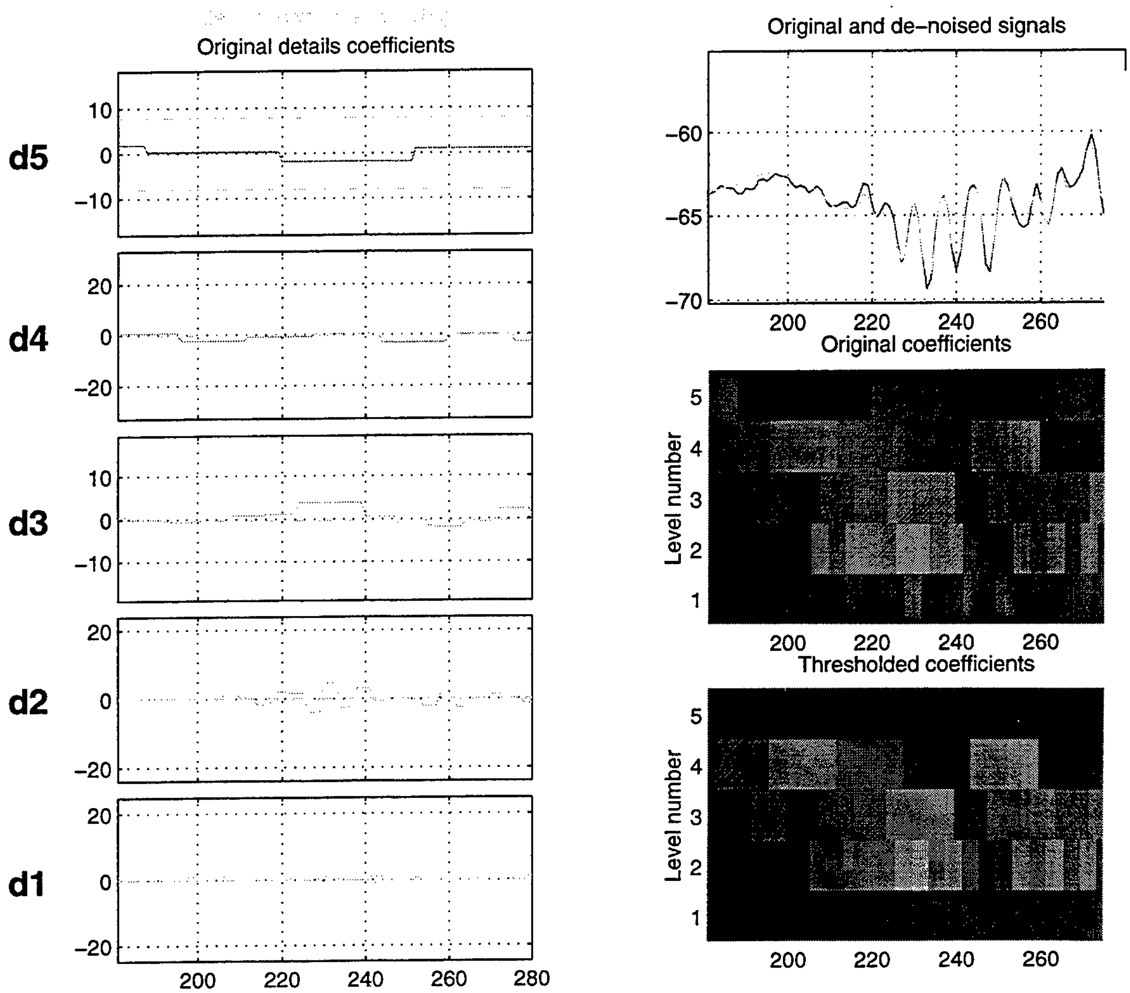

Figure 19. Wavelet decomposition of the Nov. 4, 1996 Tyrone event r distinguishing Pn.

higher values of the coefficients. On level 2, the arrival of the Pn wave from the November 4, 1996 Tyrone event is evident as a lighter color on the image. The wavelet transform offers distinct advantages over the Fourier transform when dealing with transient seismic signals such as those shown above.

Figure 20 shows the results of wavelet processing on the PnPn signal from the Tyrone event shown in Figure 18. The PnPn arrival is evident on level 3 as seen in the lower right hand plot of the figure.

Figure 21 shows an infrasound signal thought to be from the December, 1996, Geminid meteor shower. The Geminid shower is active between December 6 and December 19 reaching peak activity on December 13. Unlike most meteor showers which are by-products of comets, the Geminid orbit does not match any known orbit for a comet. However, the Geminid orbit does match the Earth-crossing asteroid 3200 Phaethon, a four-mile wide object discovered in 1983. Thus the Geminids are the first meteor shower to be positively linked to asteroids. Hourly rates during the peak observation time are 80 per hour. The maximum amplitude of this signal is approximately 20 μbars, one of the largest infrasound event recorded at TXAR to-date. SMU personnel at TXAR between December 9 and December 13 reported sighting many meteors.

Figure 22 is a plot of the arrival times for over 127 infrasound signals recorded at TXAR on December 12, 1996 plotted against backazimuth. All of these acoustic signals could not be associated with a seismic event, and are thought to be from meteors from the Geminid shower entering and causing acoustic disturbances in the upper atmosphere northwest of TXAR (290-340 degrees). The gap in the data between 2:00 and 14:00 GMT could be related to the zonal wind effect discussed earlier. Half of the day's events should be in the atmosphere northeast of TXAR, and thus would be attenuated by strong winds in the upper atmosphere.

Figure 23 shows the results of calculating the semblance between traces for a Geminid acoustic event on December 12, 1996. The upper plot shows the TXAR seismic and acoustic array data aligned to 0.35 km/sec, shifted to a

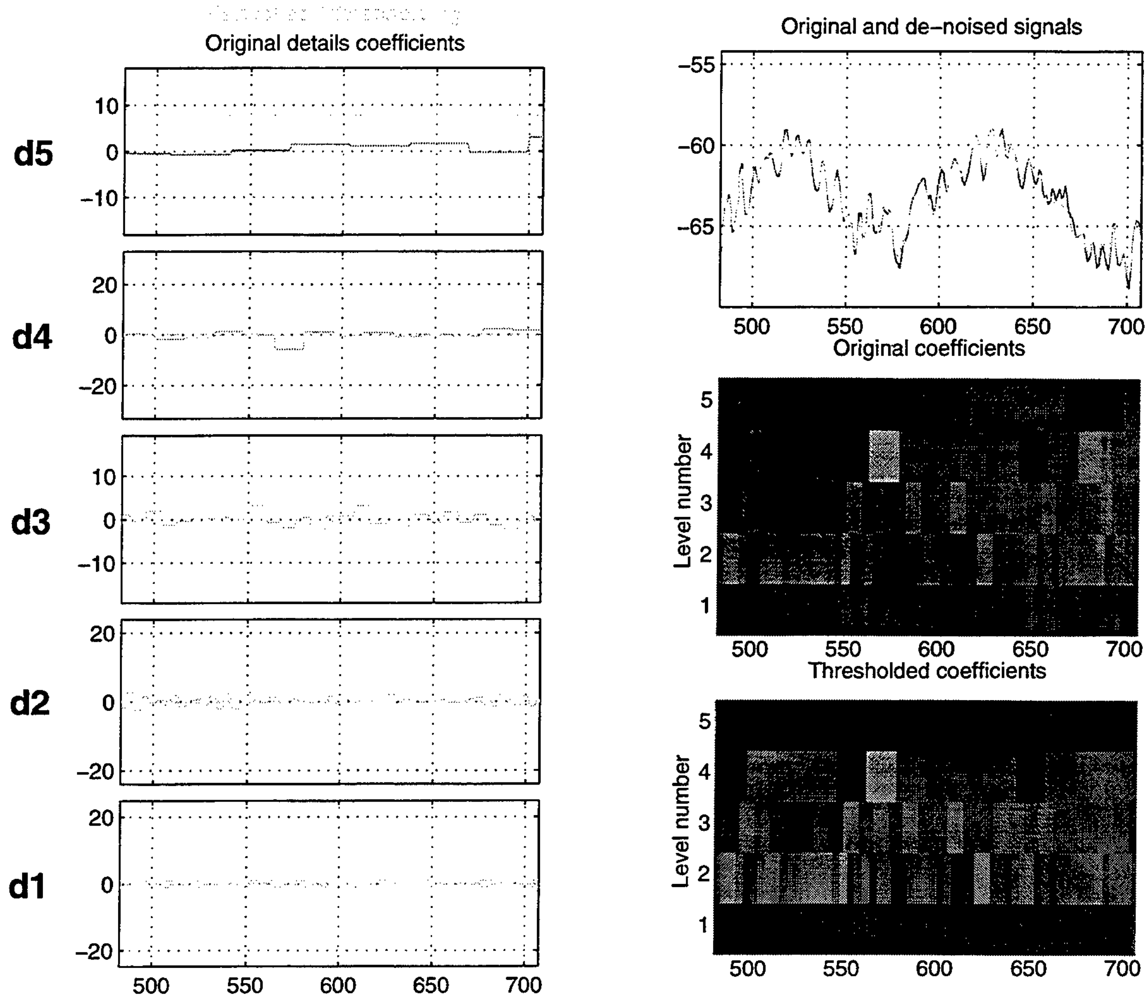

Figure 20. Wavelet decomposition of the Nov. 4, 1996 Tyrone event to distinguish PnPn.

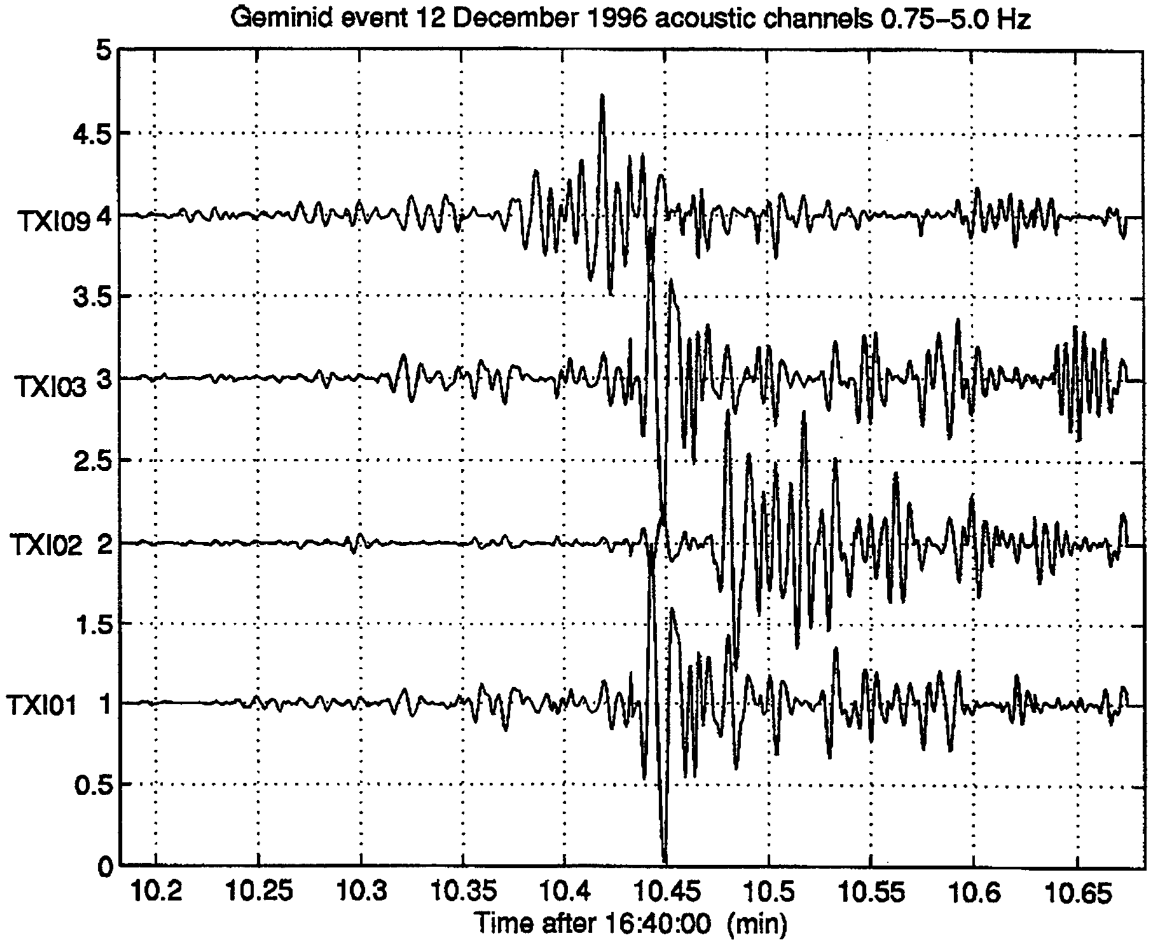

Figure 21. Infrasound signal thought to be the result of the Geminid meteor shower of December, 1996.

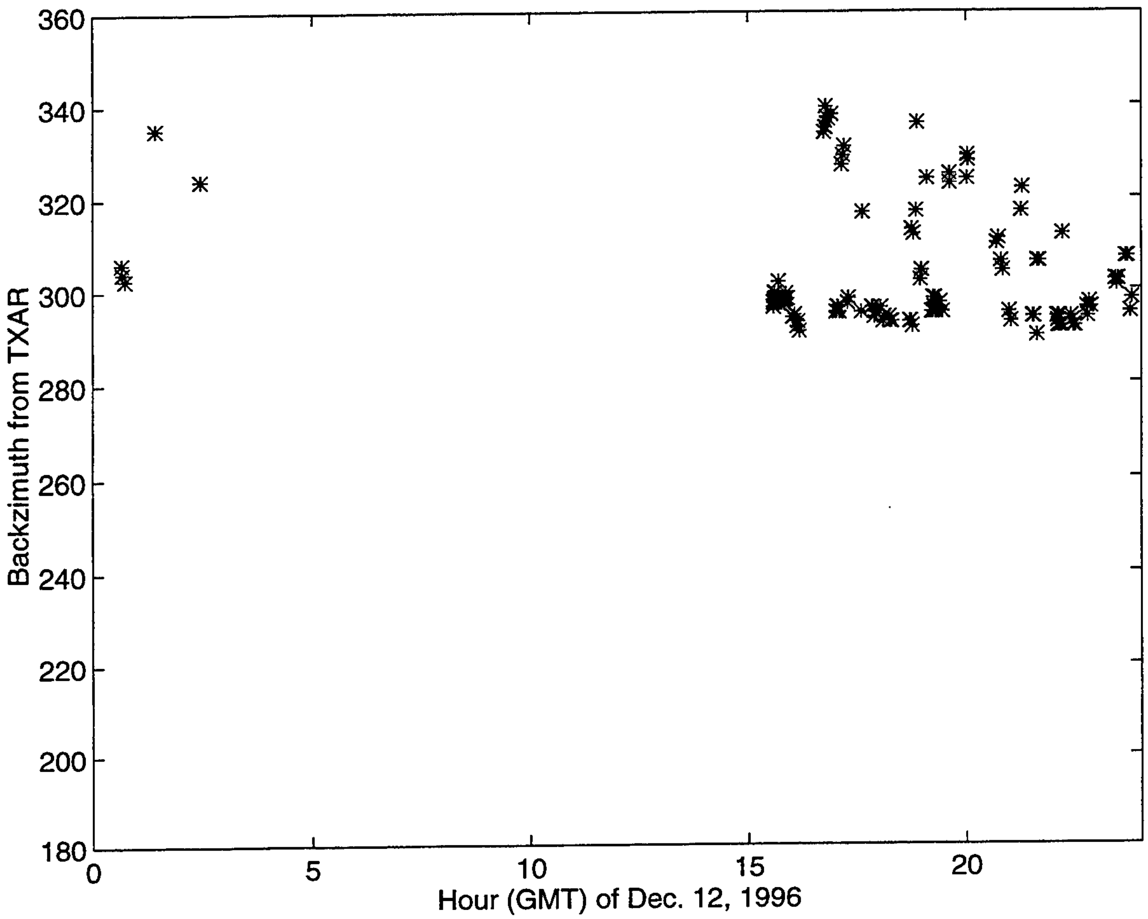

Figure 22. Arrival times for infrasound signals recorded on Dec. 12, 1996 plotted against backazimuth. These events are suspected to be from the Geminid meteor shower.

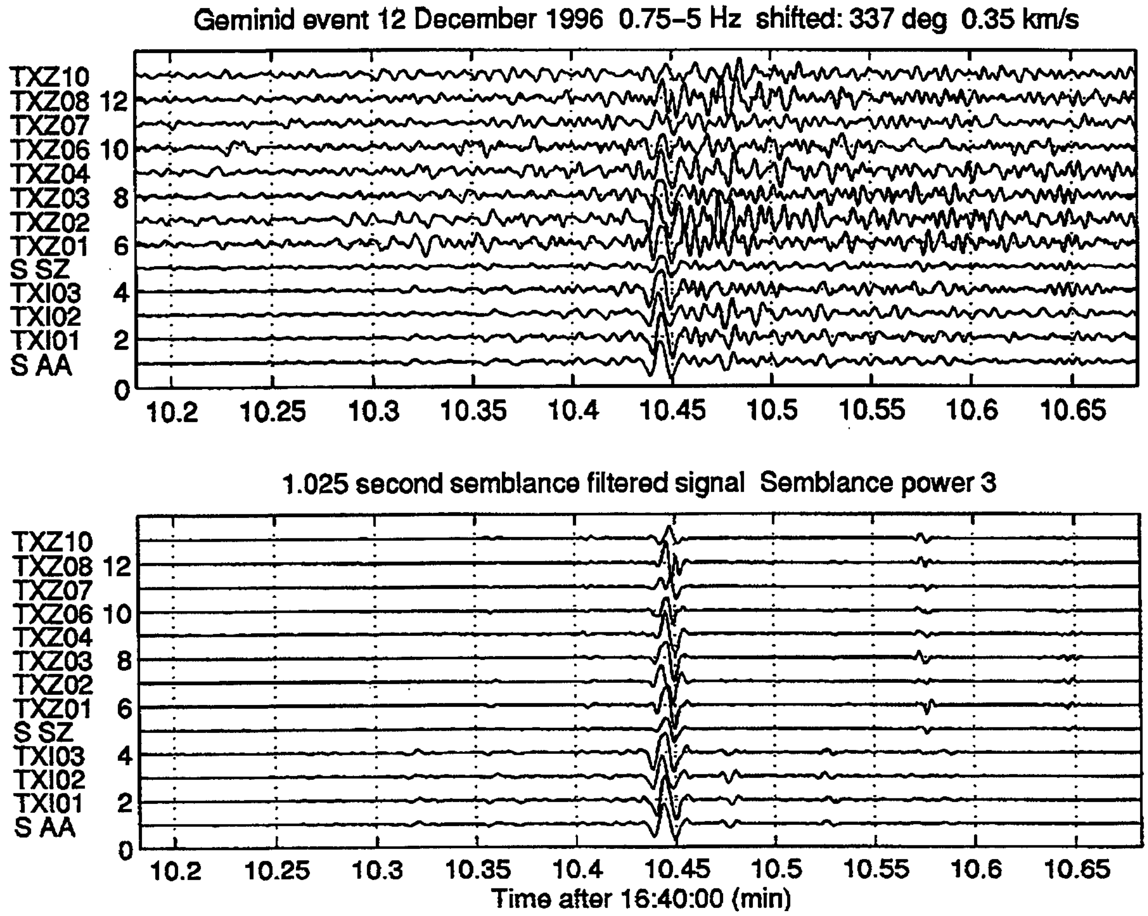

Figure 23. Semblance studies for a suspected Geminid acoustic event.

backazimuth of 337 degrees, and band pass filtered between 0.75 and 5 Hz. Note that seismo-acoustic signature is visible on the seismic channels (TXZ01-TXZ10). The lower plot shows how the semblance method enhances the acoustic signal in both the acoustic and seismic domains.

Figure 24 is a plot of a seismic event on February 11, 1997 originating within 10 km of the TXAR seismic array (TX01/sz-TX10/sz). For several years, events such as this have been labeled as microseismicity along faults in the vicinity of TXAR. Implementation of the TXAR acoustic array (TXI01, TXI02 , TX103, TXI09) in March, 1996, has allowed us to determine the origin of these events, with duration magnitudes < -0.5, to be explosions southwest of Terlingua, Texas. The data are plotted at uniform scales to show how the amplitudes are attenuated by an order of magnitude or more as the signals sweep across the array. This attenuation is better illustrated in Figure 25, which shows a contour plot of the maximum amplitude (DC to peak) of the P waves.

Figure 26 shows the arrival of a low-pressure storm front at TXAR on February 13, 1997. The front arrives from the north (22:42:50 at TXI09) and increases the noise greatly on both the seismic and acoustic arrays following its passage. For scale, the seismic signal prior to the front is a m_b=2.8 explosion from the MICARE mining district of northern Mexico. Had the seismic signal been after the storms arrival at TXAR, processing would have been somewhat difficult.

Local Explosion-- February 11, 1997

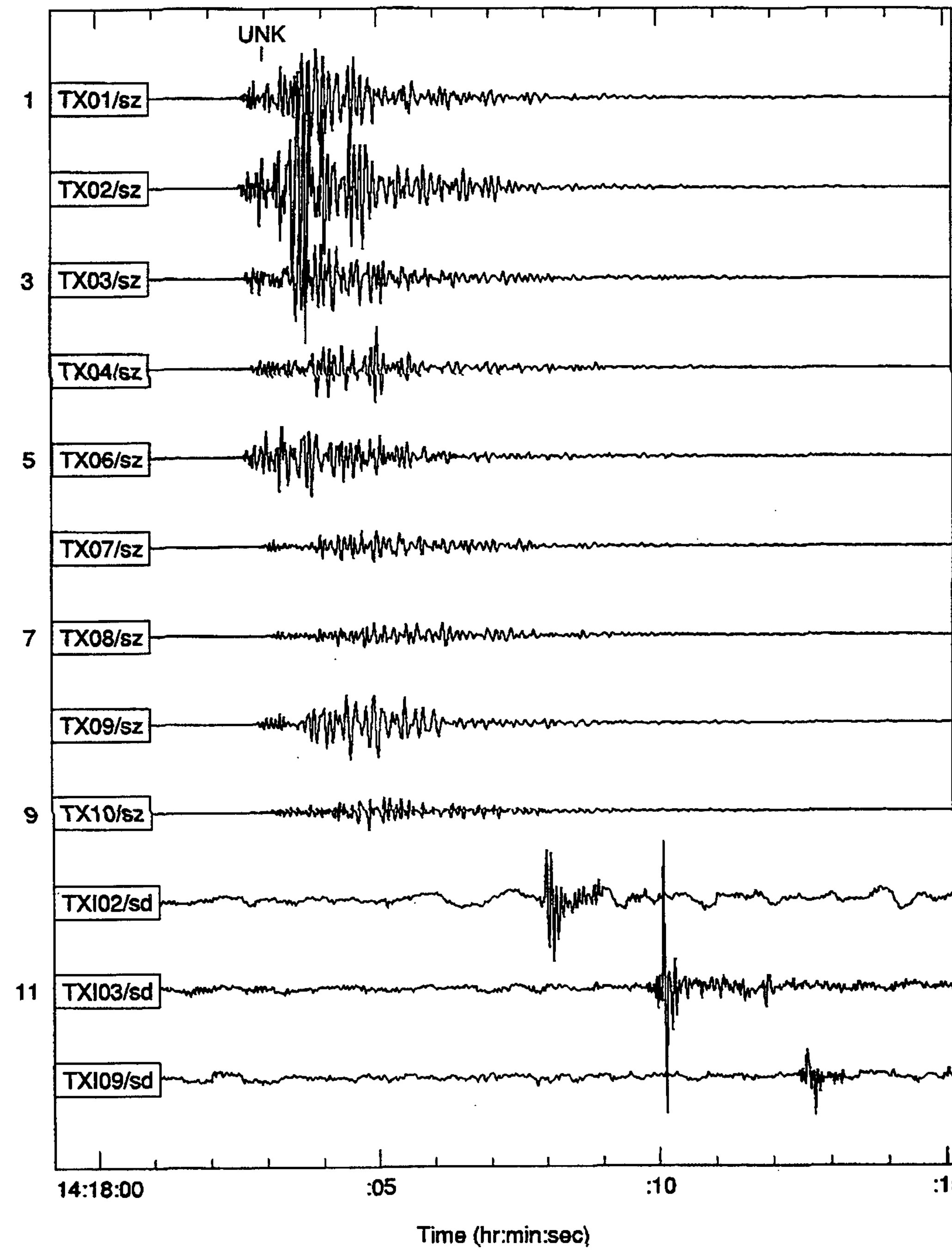

Figure 24. Local seismic event thought to be from an explosive source due to associated infrasound signals.

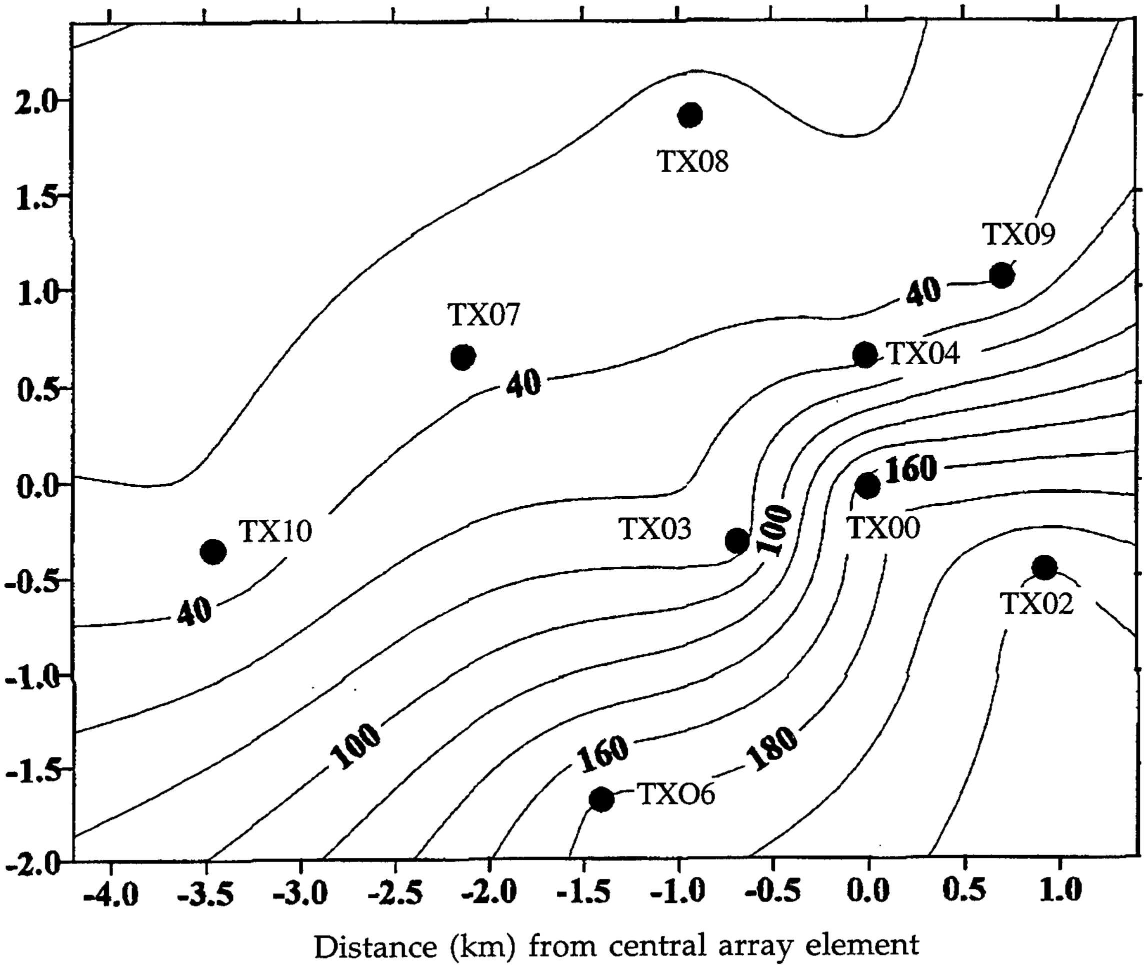

Figure 25. Amplitude contours (maximum amplitude in counts (DC-peak)) for P waves from a local explosion on Feb. 11, 1997. TXAR array stations are shown as black dots.

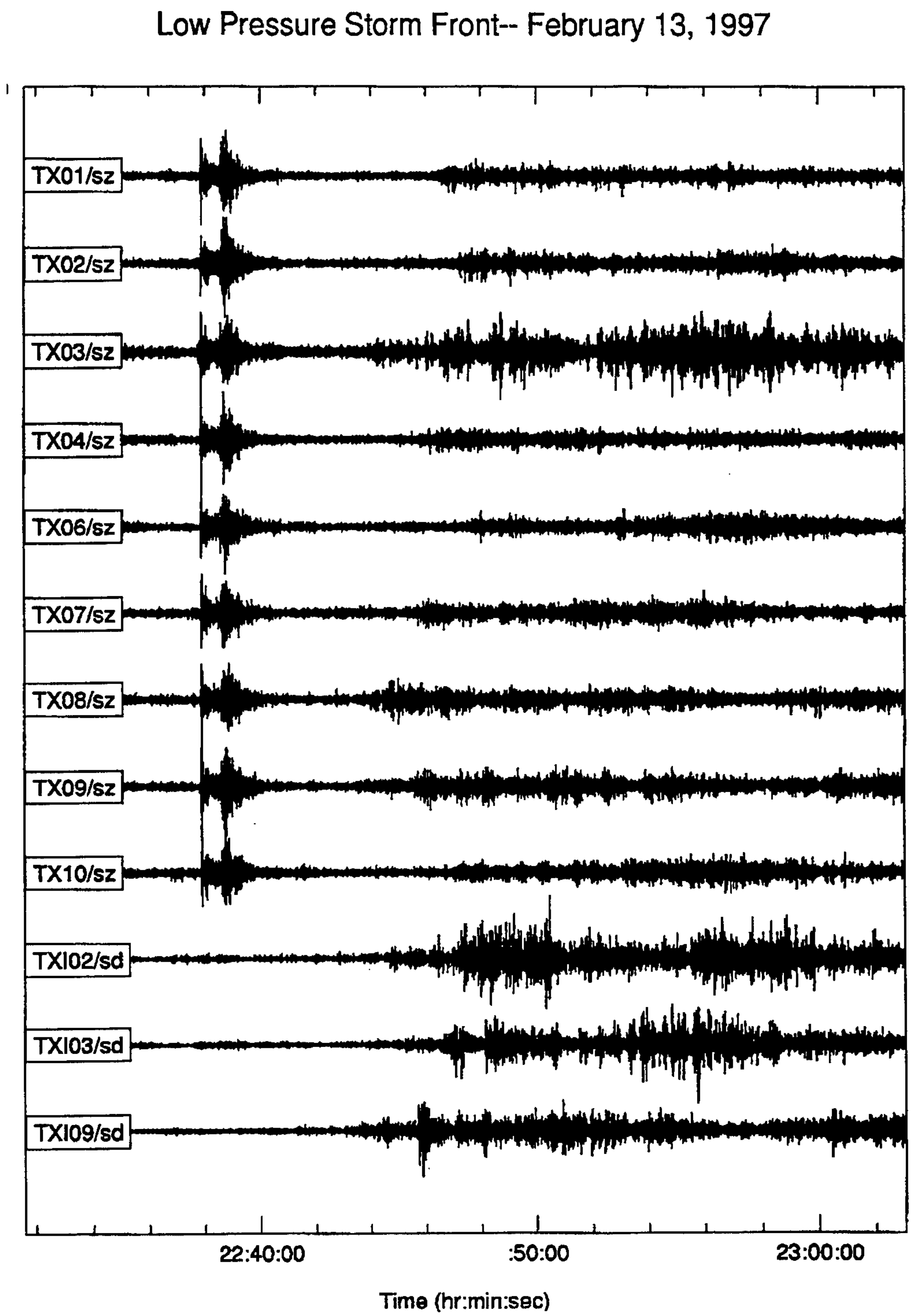

Figure 26. Arrival of a weather front at TXAR on Feb. 13, 1997. Noise levels are significantly increased on the seismic and acoustic channels as a result of the storm's passage.

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2.5 ACKNOWLEDGMENTS

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3.1 PREVIOUS CONTRACTS AND PUBLICATIONS

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3.1.1.1.ARPA Contract # MDA 972-88-K-0001

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Quarterly R&D Status Report, 1 Feb. through 30 Apr. 1990.

Quarterly R&D Status Report, 1 May through 31 July 1990.

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3.1.1.3 Contract # 19628-93-C-0057

Design, Evaluation, and Construction of TEXESS and LUXESS, and Research in Mini-Array Technology and Use of Data from Single Stations and Sparse Networks

Quarterly R & D Status Report, 30 April to 31 July 1993.

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